NASA AERONAUTICS RESEARCH INSTITUTE

Affordable Flight Testing of LEAPTech

(Leading Edge Asynchronous Propeller Technology)

Distributed Electric Propulsion

Presenters

Mark Moore: NASA Langley

Sean Clarke: NASA Armstrong

Alex Stoll, Alec Clark, Scott MacAfee: Joby Aviation

Trevor Foster: ESAero

With many other major contributors at LaRC, AFRC, Ames, GRC, Joby, ESAero

NASA Aeronautics Research Mission Directorate (ARMD)

2015 LEARN/Seedling Technical Seminar

January 13–15, 2015

Outline

Innovation/Technical Approach/Impact - *Mark Moore/NASA LaRC*

Results:

Aero-Propulsive Wing/Propeller Design/CFD - *Alex Stoll/Joby Aviation*

Motor, Controller, Propeller Development - *Scott MacAfee/Joby Aviation*

Truck Test Rig, Wing Fabrication and Integration - *Alec Clark/Joby Aviation*

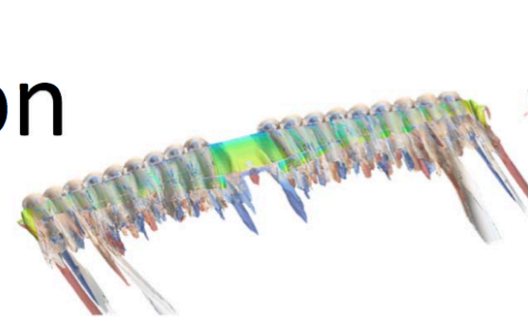
Wing Instrumentation, Calibration, Preparation - *Trevor Foster/ESAero*

Power System, Safety Review, Initial Testing - *Sean Clarke/NASA AFRC*

Information Distribution/Next Steps - *Mark Moore/NASA LaRC*

Questions - *All*

Innovation



WHAT ARE WE TRYING TO DO?

- Understand how Distributed Electric Propulsion (DEP) enables new vehicle capabilities through tight coupling of propulsion to the entire vehicle system, with initial focus on the highlift system, aerodynamics, acoustics, control, structures, and aeroelastics.
- Show the DEP integration benefits/penalties through comparison to existing aircraft, with a focus on early adopter markets such in General Aviation to provide a certification basis for the new technology to be applied to commercial aviation.

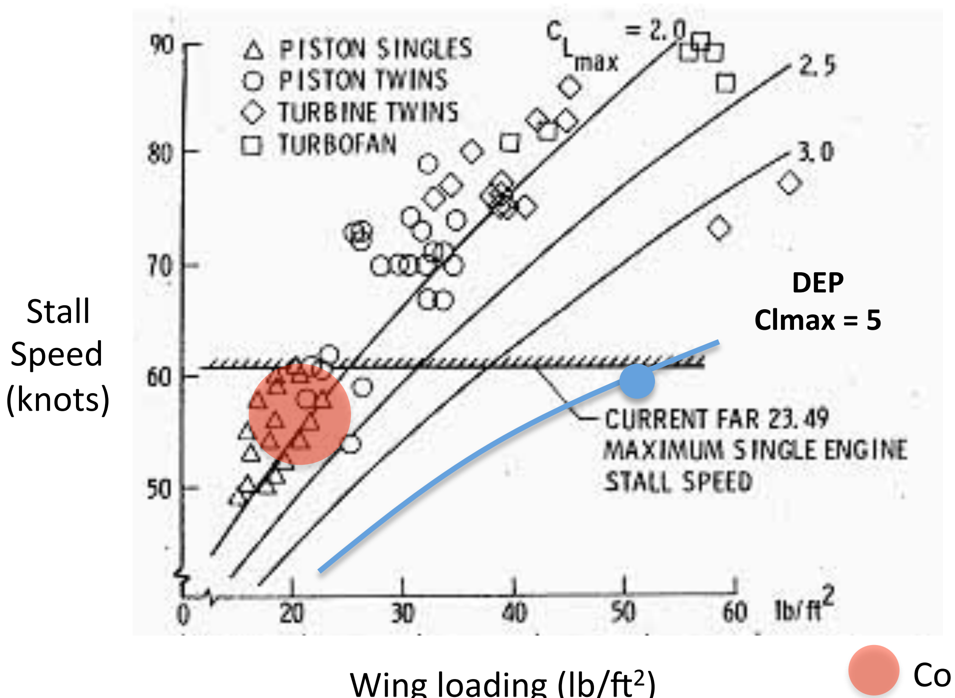
HOW DOES THIS GET DONE, AT PRESENT?

- Current propulsion is integrated in an isolated manner and attempts to minimize the multi-disciplinary coupling.
- The automobile industry is currently leading the development and application of electric technologies, showcasing how new degrees of freedom are opened for vehicle design.

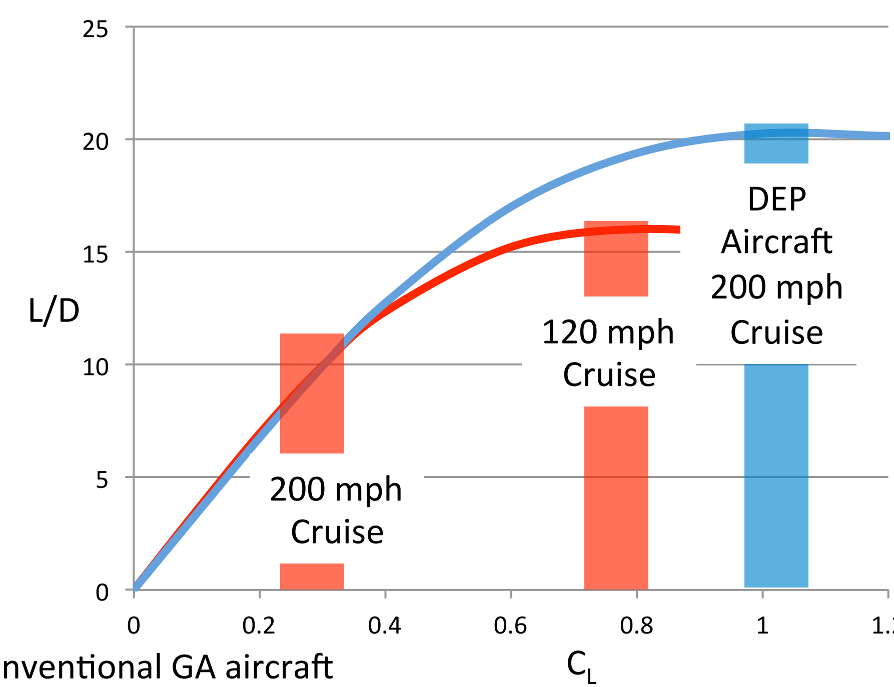
Technical Approach

Increasing wing loading is critical for achieving high aerodynamic efficiency at high speed

Stall Speed vs Wing Loading (General Aviation Aircraft)



Lift/Drag Ratio vs Cruise C_L (GA Aircraft)

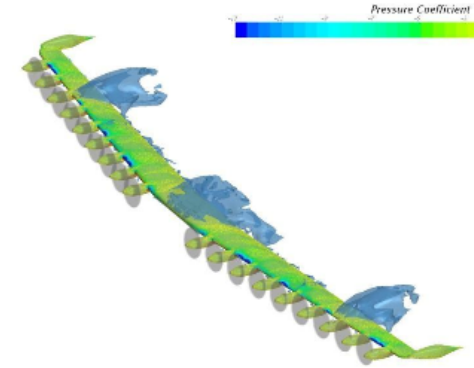


Conventional GA aircraft

DEP GA aircraft

Technical Approach

- Conduct aero-propulsive design and analysis of a highly integrated wing-propeller system using a variety of CFD analytical tools.
- Design and fabricate a mobile ground truck rig that can permit full-scale testing with sufficient accuracy.
- Develop and conduct component tests of the motors, controllers, propellers, energy, and power system.
- Design and assemble the instrumentation system.
- Design the structure and fabricate the wing.
- Integrate the nacelles, motor, controllers, propellers, and onboard wing instrumentation.
- Calibrate the load balance on the truck, debug the fully integrated wing and truck system.
- Conduct a NASA AFRC review to assure safe testing.
- Conduct initial low-speed and then high-speed testing.

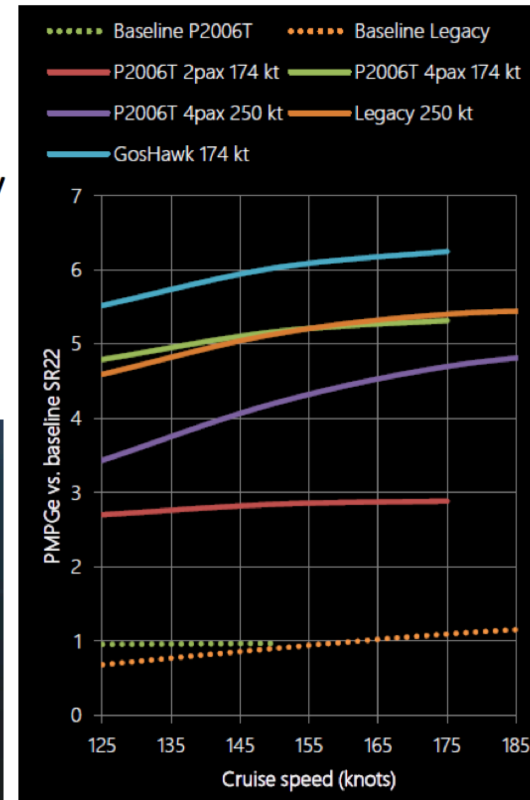


Impact

Make Aircraft <u>More Efficient</u>, with <u>Improved Emissions</u>, <u>Noise</u>, <u>Ride Quality</u>, <u>Safety</u>, and <u>Operating Costs</u>

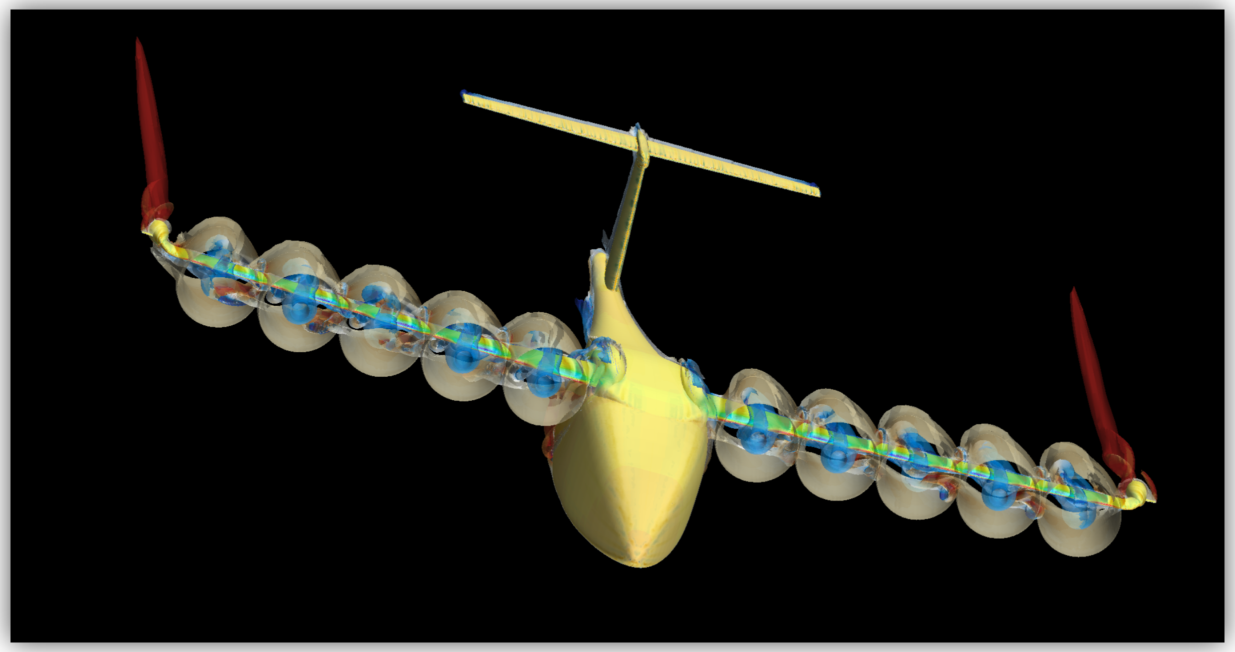
- Typically achieving an improvement in one aircraft capability requires taking penalties in other areas.
- By leveraging this new integration technology, Distributed Electric Propulsion (DEP), dramatic improvements are possible across these areas, while only absorbing penalties in range and weight (which penalties will become significantly reduced as battery specific energy improves).
- Applying DEP to a General Aviation aircraft enables these improvements, while limiting the range to 200 miles and increasing the vehicle weight from 2700 lb to 3400 lb.

Aerodynamic Efficiency: Lift/Drag ratio improved from 11 to 17
Propulsive Efficiency: Energy conversion efficiency from 24% to 83%
Emissions: Life cycle GHG decreased by 5x using U.S. average electricity
Community Noise: Certification noise level from 85 to <65 dB
Safety: Highly redundant propulsion system
Ride Quality: Wing loading increased by >2.5x
Operating Costs: Energy costs decrease from 45% to 12% of TOC



Aero-Propulsive Wing and Propeller Design

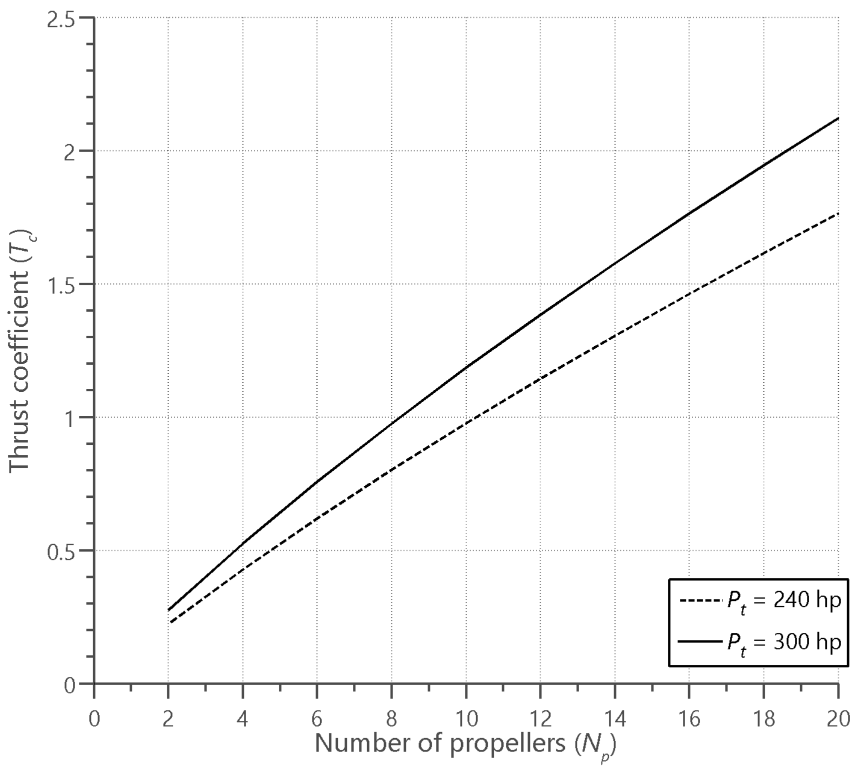
Alex Stoll, Joby Aviation

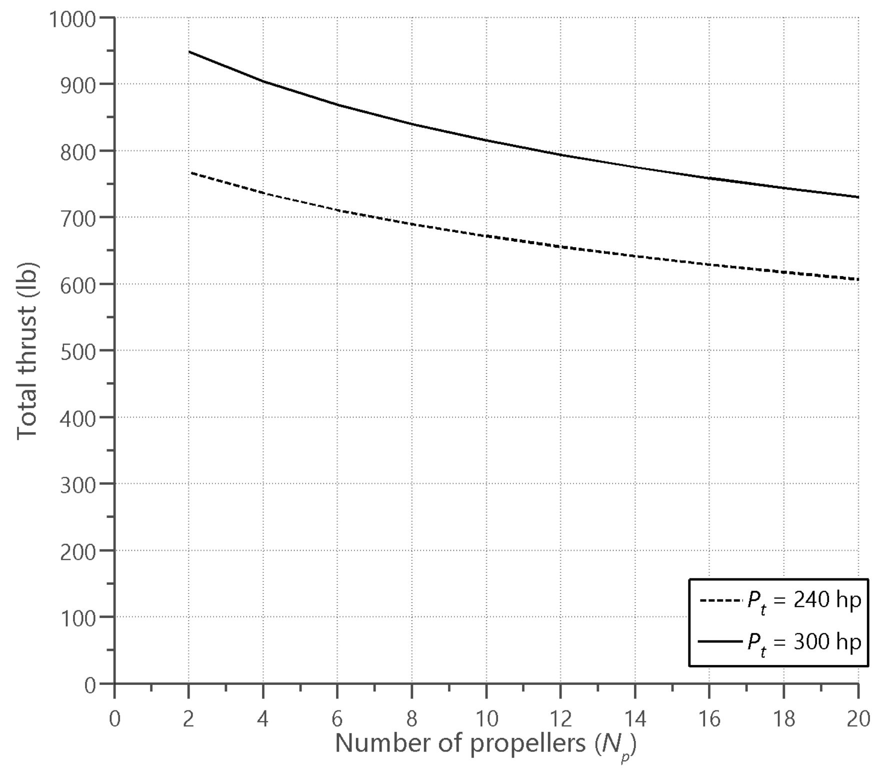


Momentum Theory Analysis

$$T_c \equiv T/q_\infty A$$

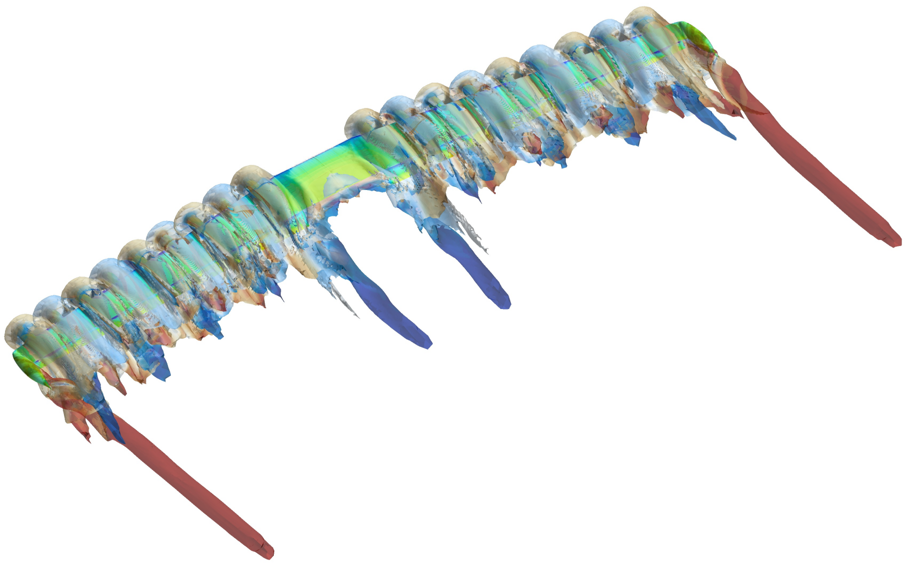
$$q_{blown} = q_\infty + T/A$$
$$q_{blown} = q_\infty (1+T_c)$$





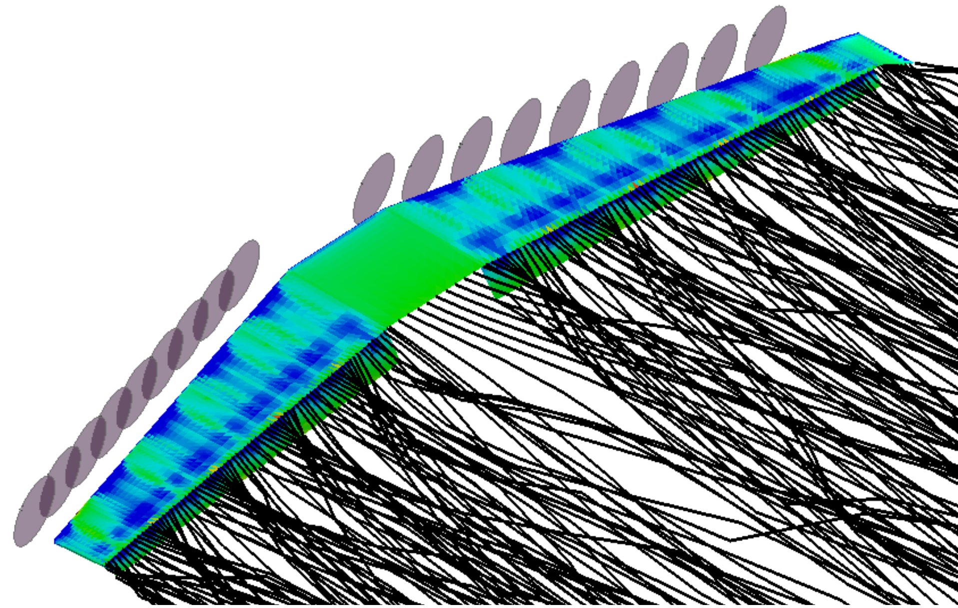
3D CFD Wing Analysis

RANS CFD (STAR-CCM+, FUN3D)



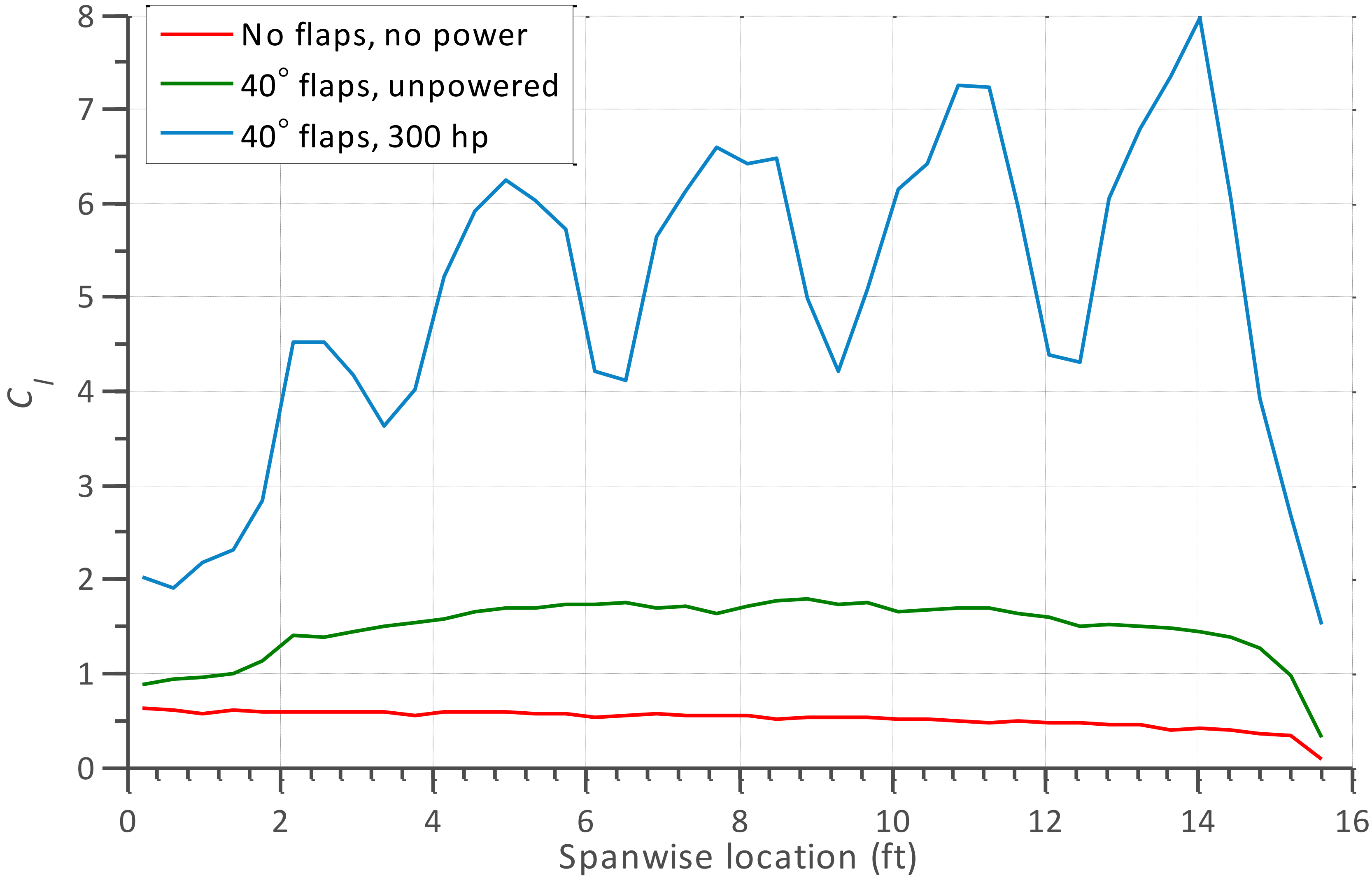
- Higher order
- More computationally expensive
- Ran with multiple turbulence models

VLM (VSPAERO)

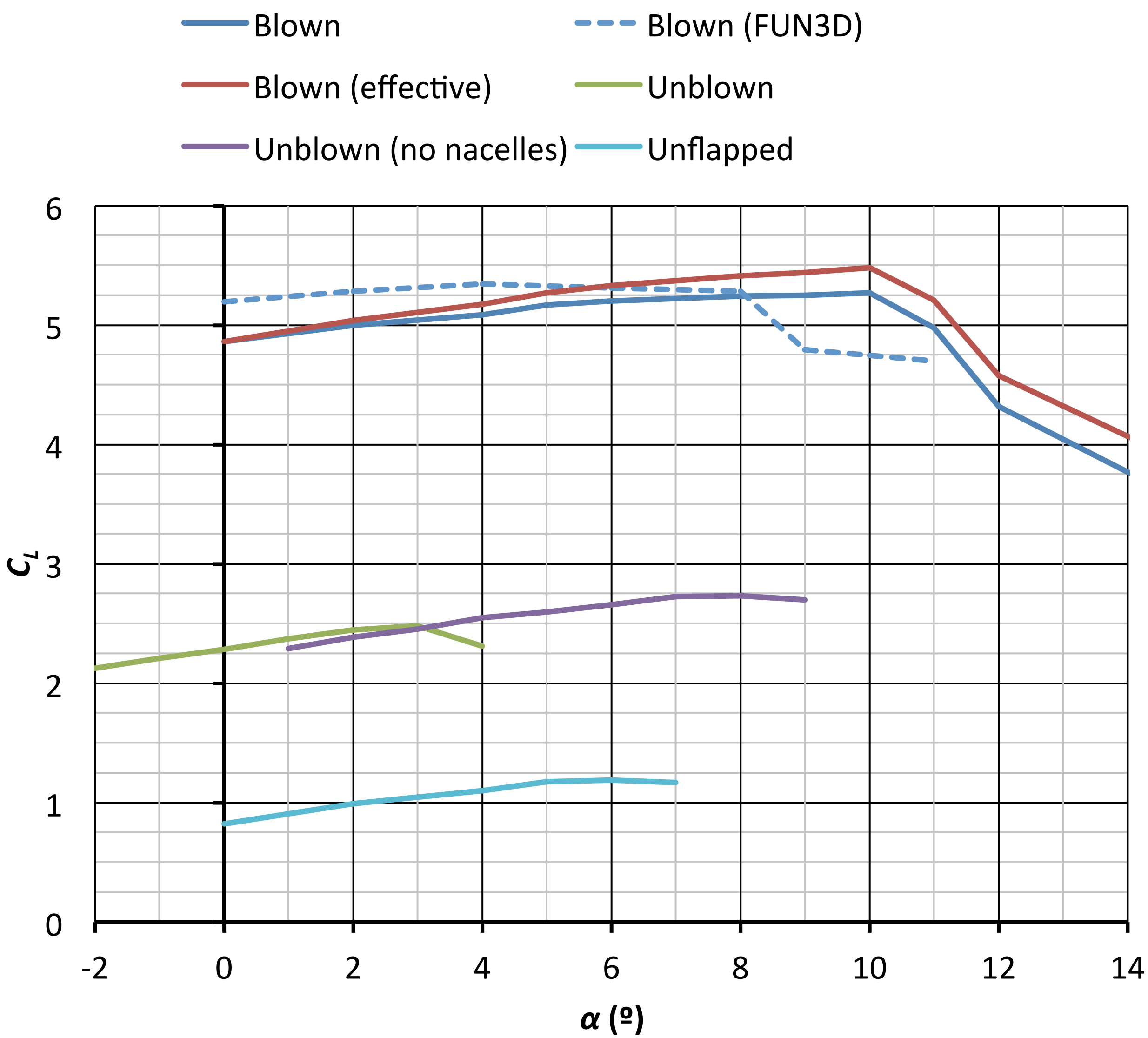


- Lower order
- Inadequate stall prediction
- Good check for other analyses

STAR-CCM+ Results (α=2º)

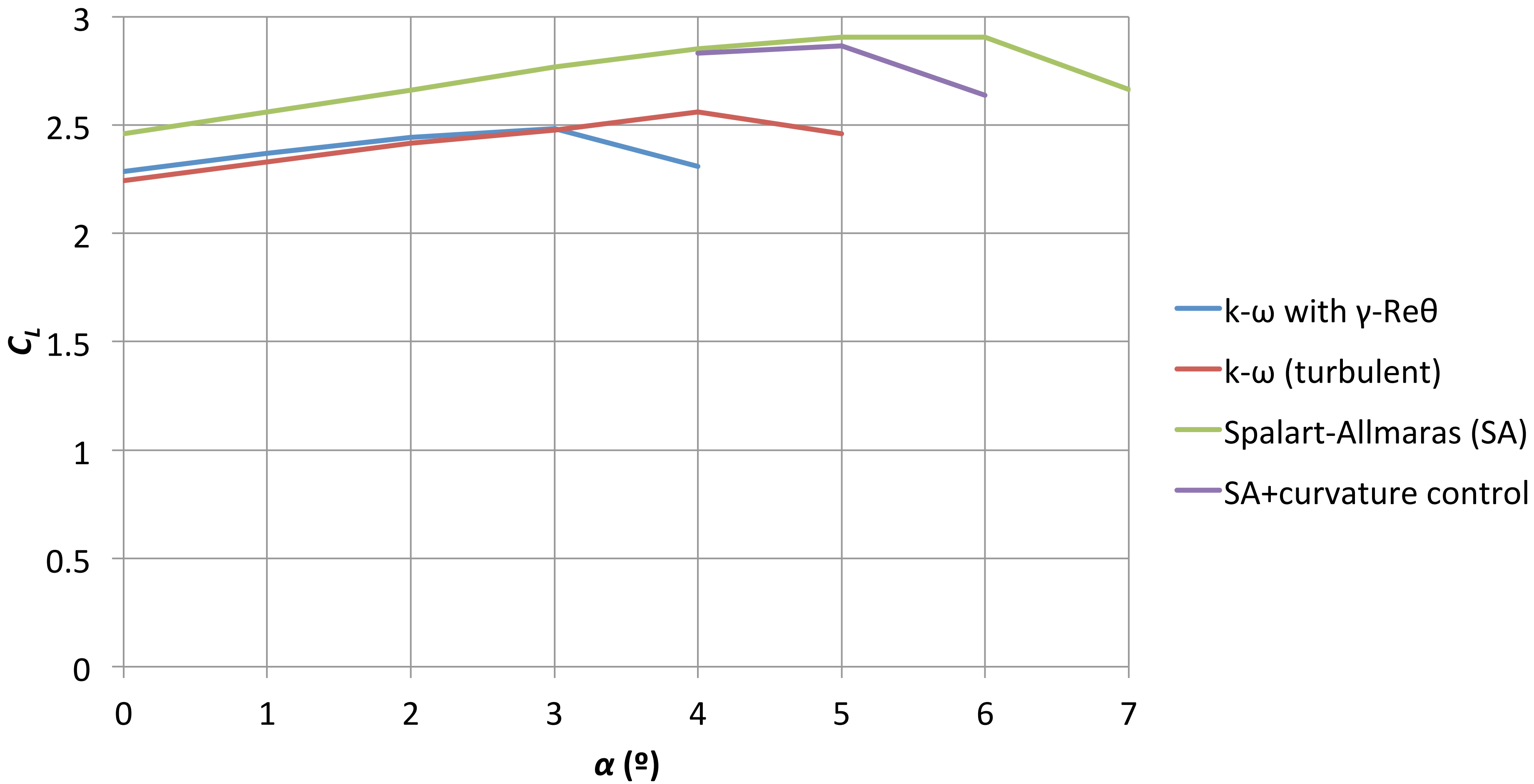


Comparison of CFD Results

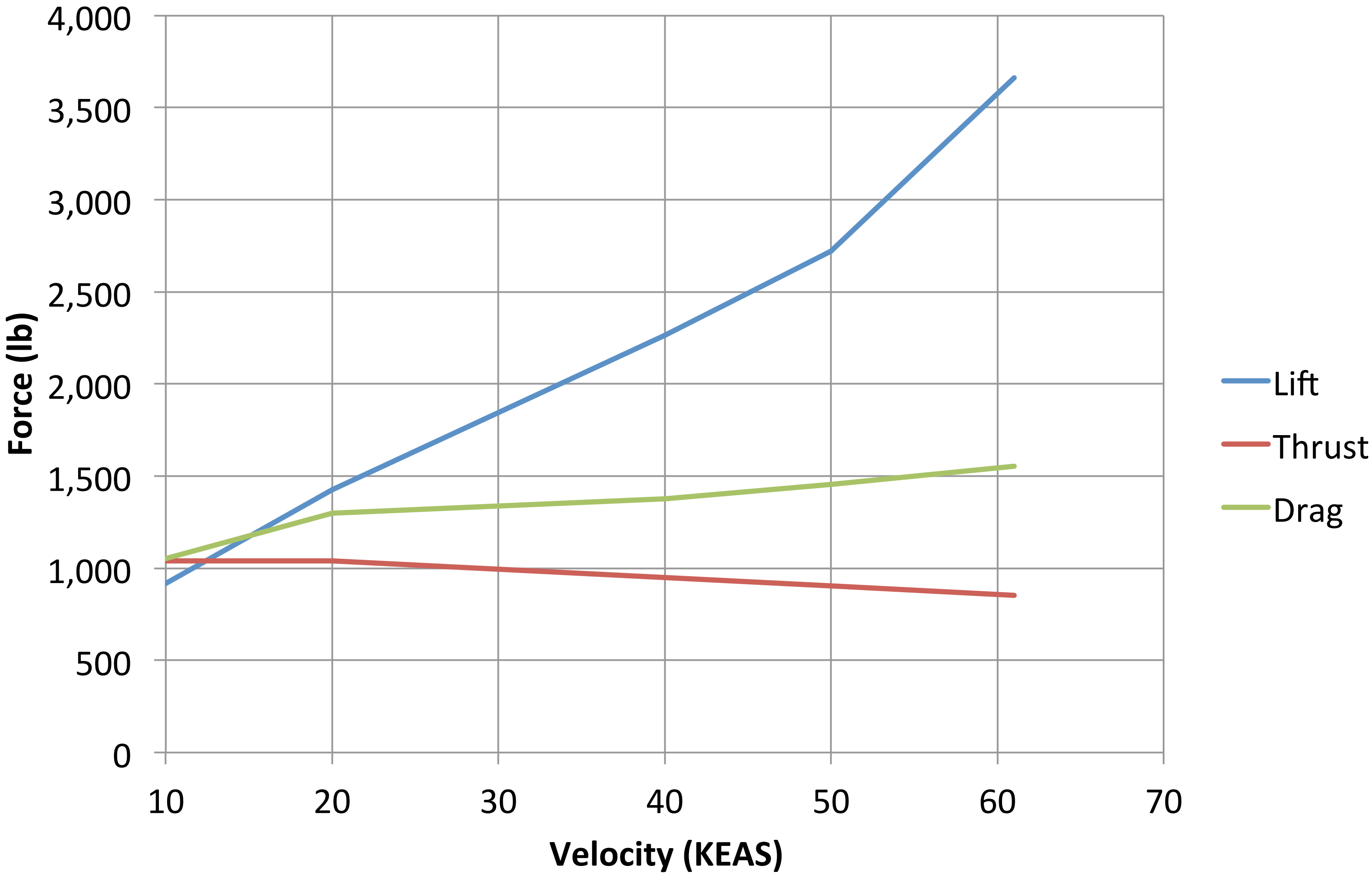


- All data are STAR-CCM+ results unless noted
- STAR-CCM+ runs use SST (Menter) k-ω turbulence model with γ-Re_θ transition model
- FUN3D runs use Spalart-Allmaras turbulence model

STAR-CCM+ Unblown Wing Turbulence Model Comparison

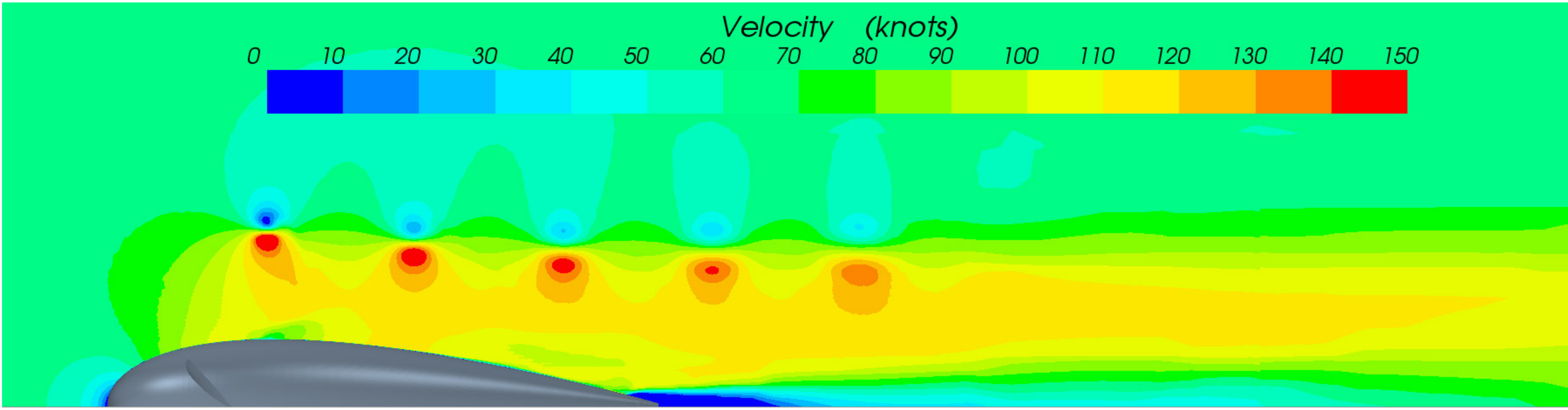


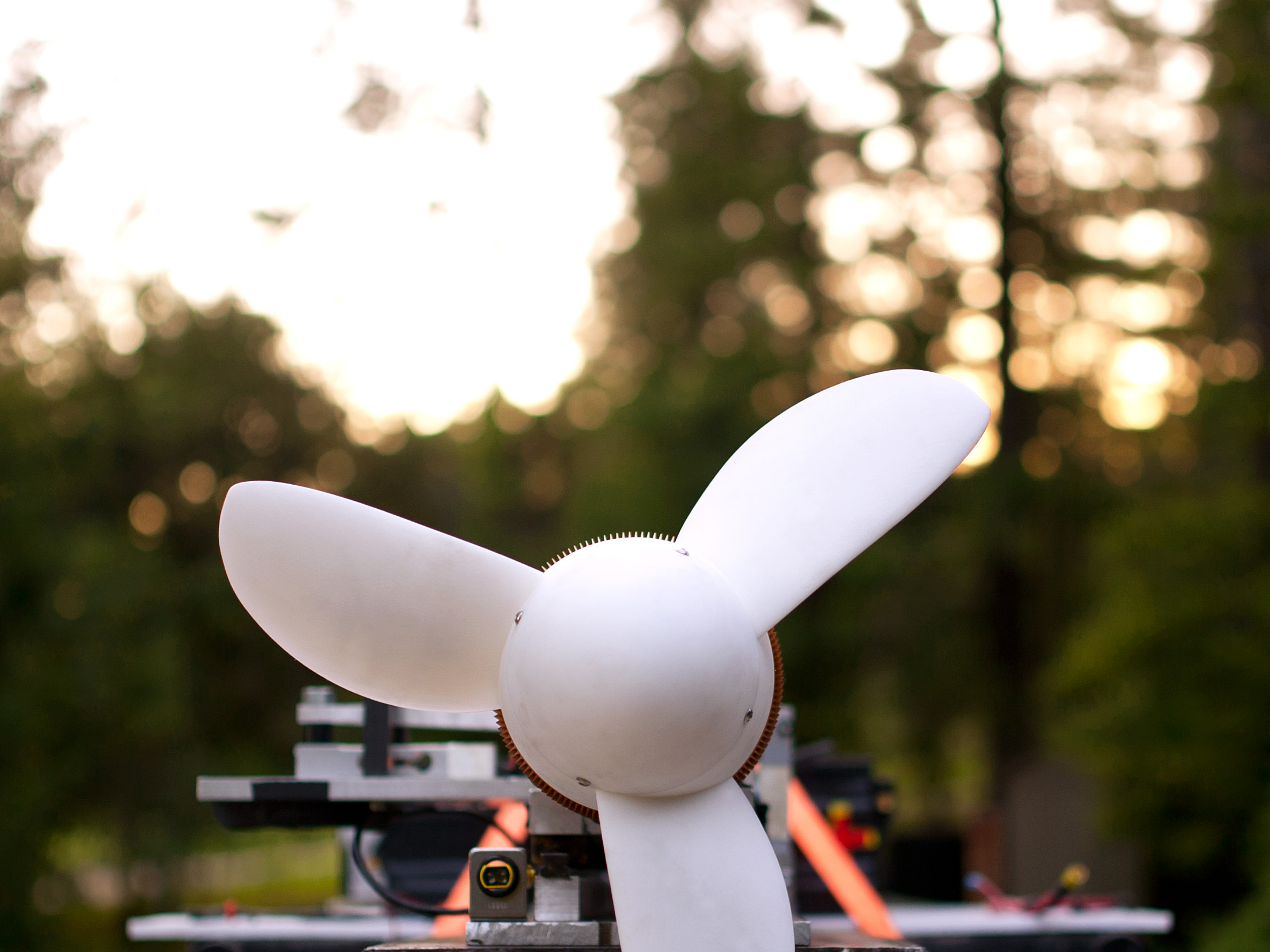
Sensitivity to V_∞ at 300 hp (α=10º, STAR-CCM+ results)



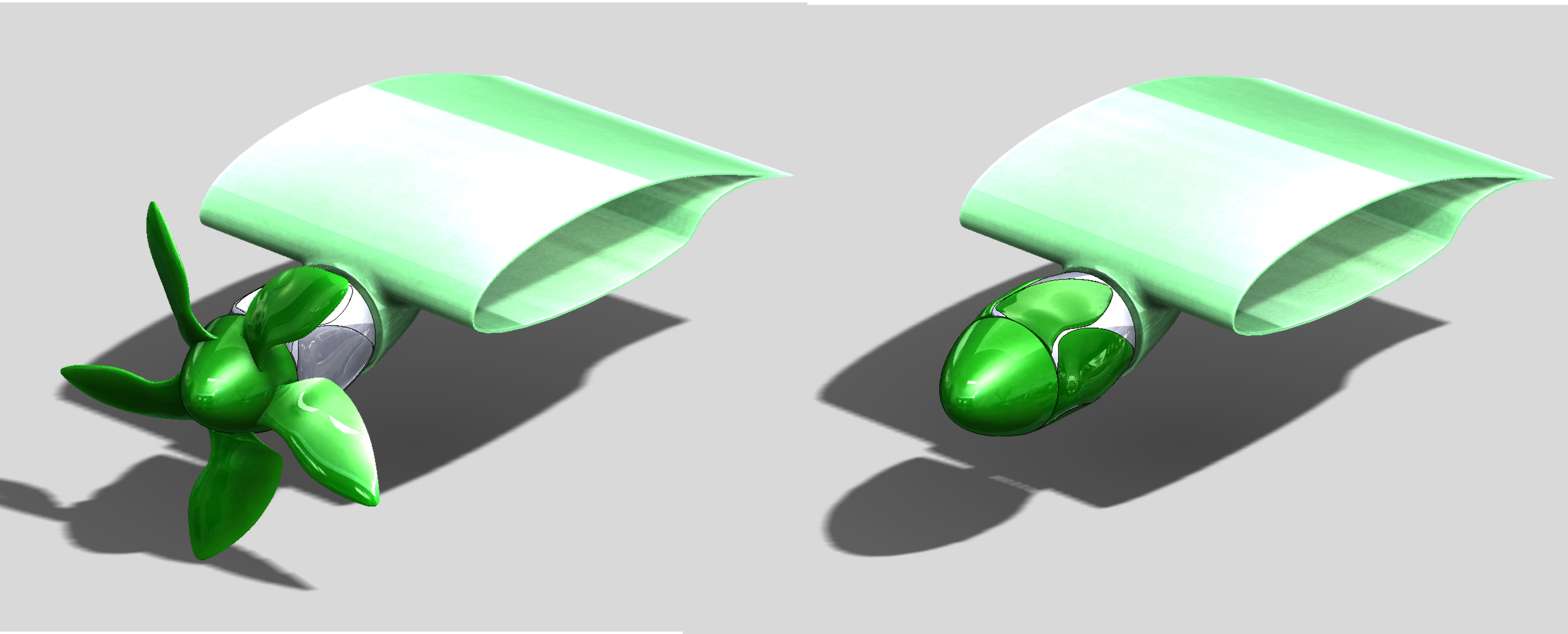
Propeller Design

- Optimized using blade element momentum theory
  - Maximize thrust in takeoff conditions
  - Remain unstalled at static conditions
  - Low tip speed (450 ft/s) to keep noise low
- Aerodynamics verified in CFD
- Initially 3 blades to reduce cost

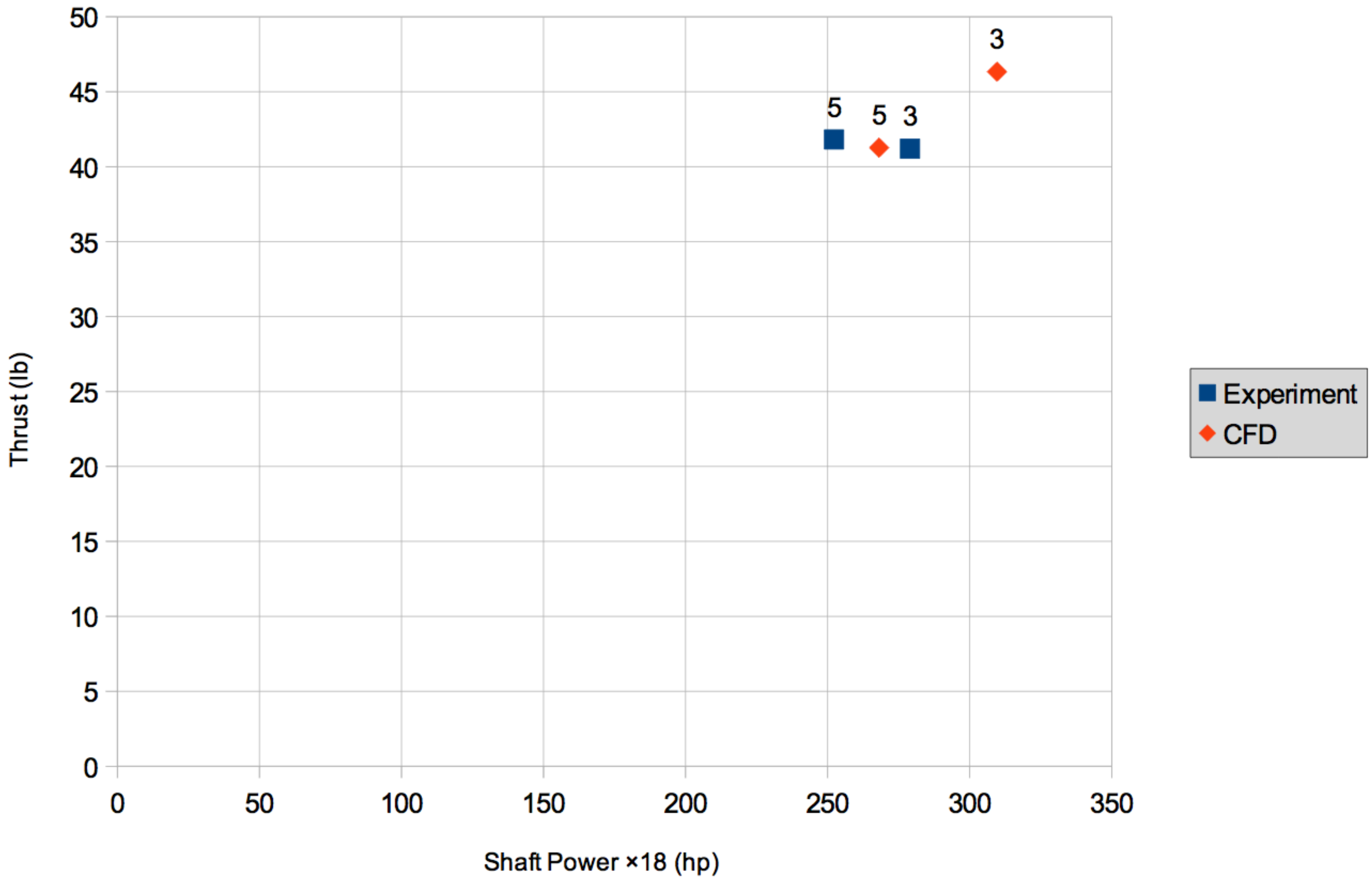




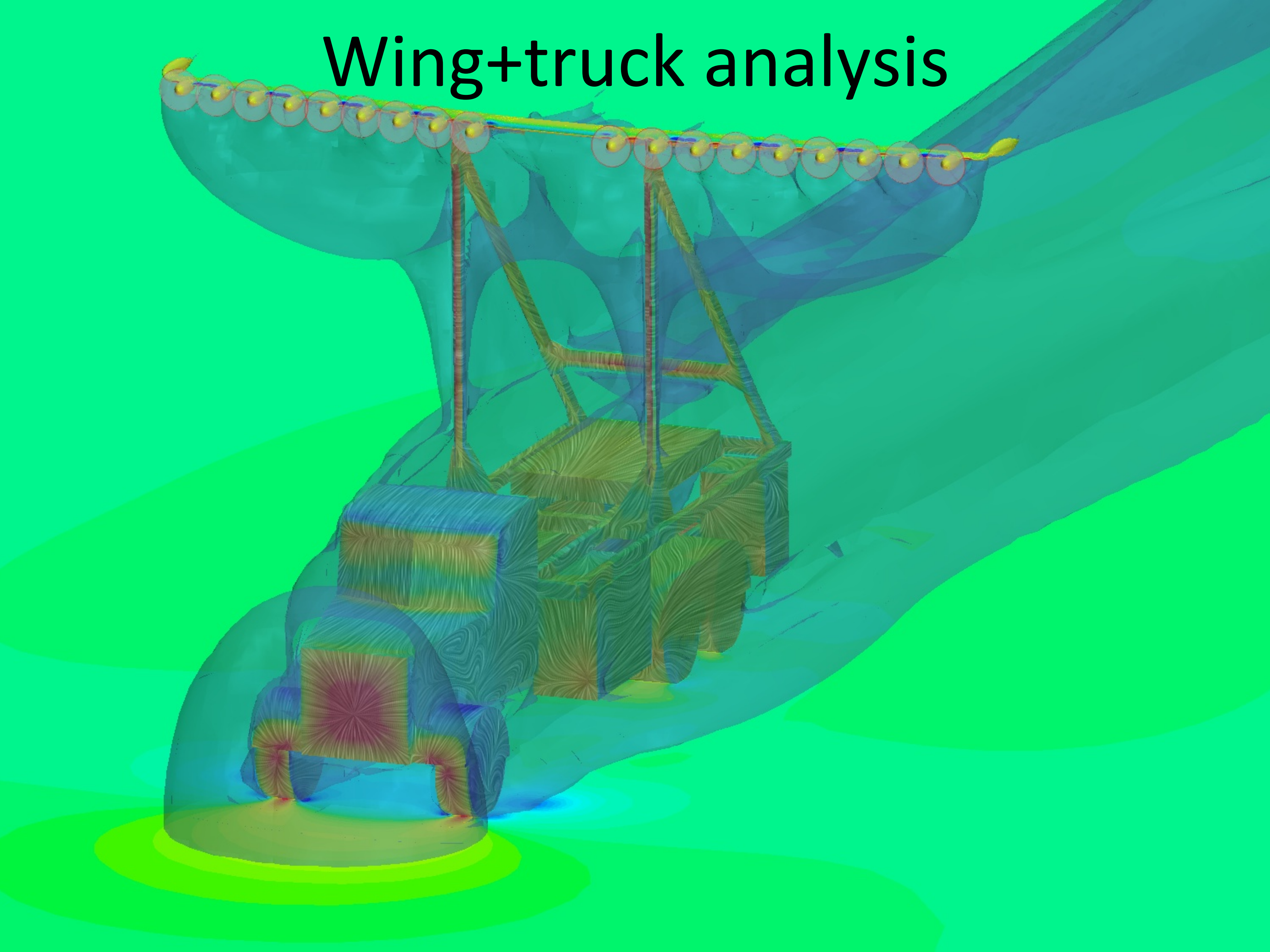
5-Blade Folding Design



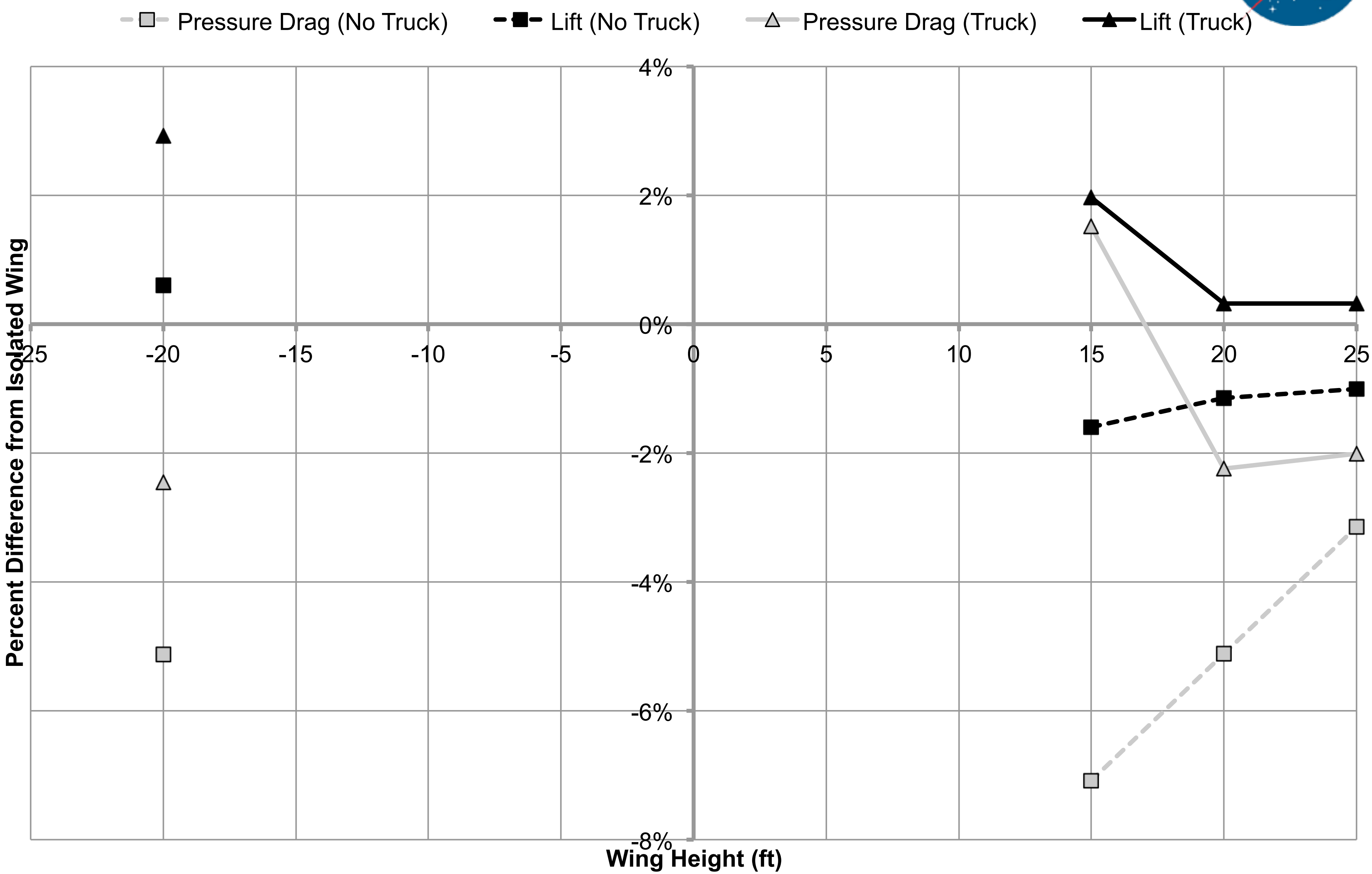
Propeller Performance



Wing+truck analysis

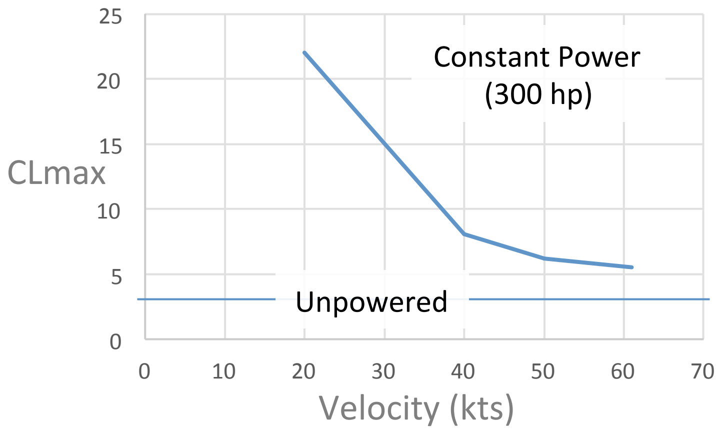


Wing Height Sensitivity CFD Results

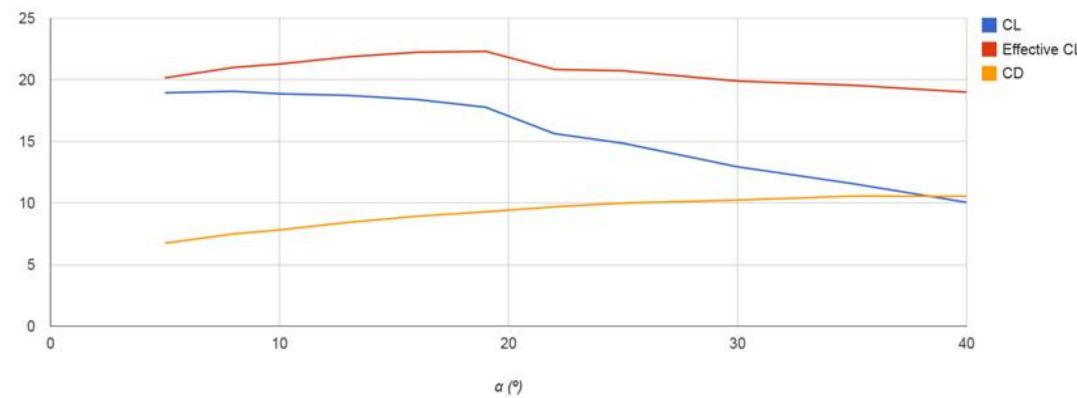


Lift vs Speed Sensitivity

Lift Coefficient
versus
Reference Speed



Lift Coefficient and Drag Coefficient @ 20 kts
versus
Angle of Attack



<u>Velocity Ratio</u>
(Vinduced/Vreference)
61 KEAS: 0.80
50 KEAS: 1.11
40 KEAS: 1.59
20 KEAS: 4.09

Motor/Controller Development
Battery Development
Component Testing

Scott MacAfee, Joby Aviation

Motor

Joby JM1

20 pole 24slot BLDC

2 turn

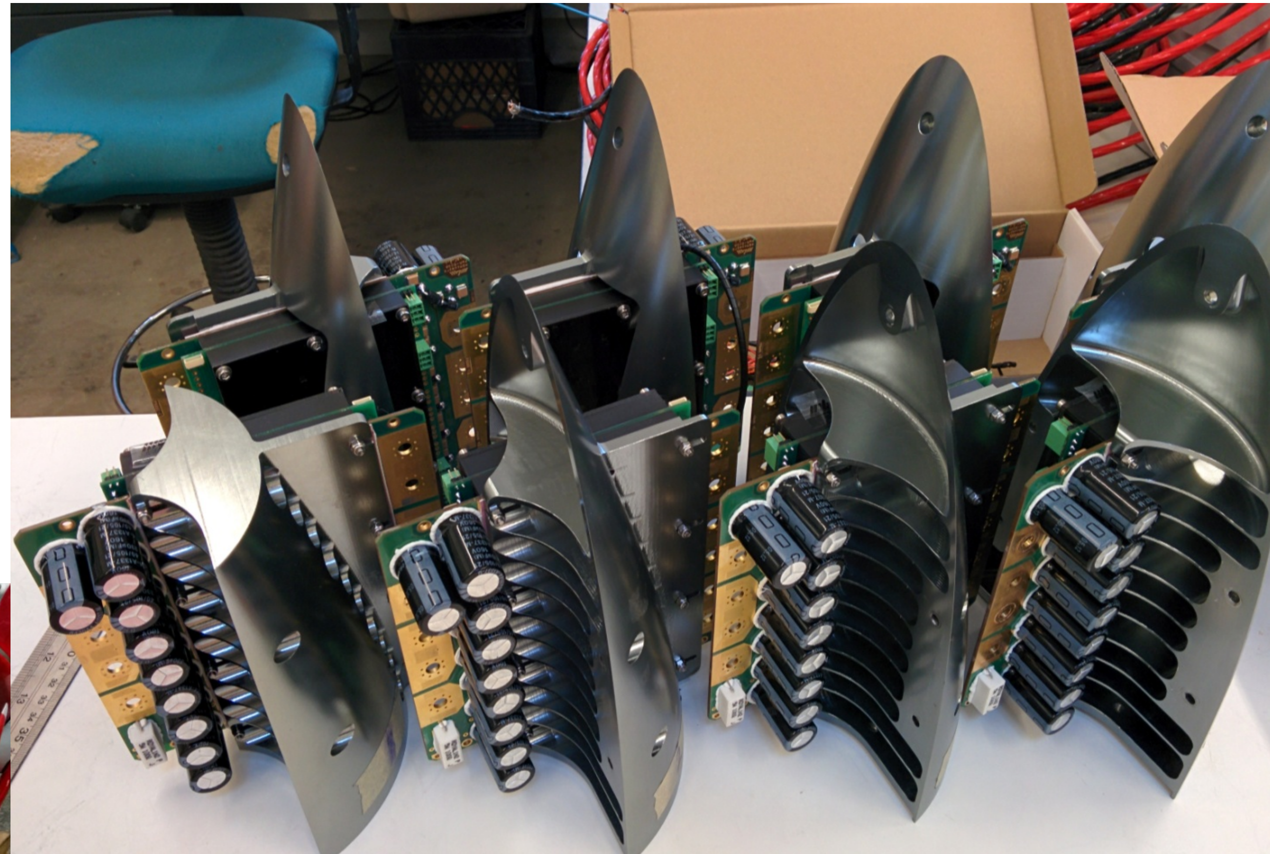
Direct drive

Controller

MGM Compro 280120

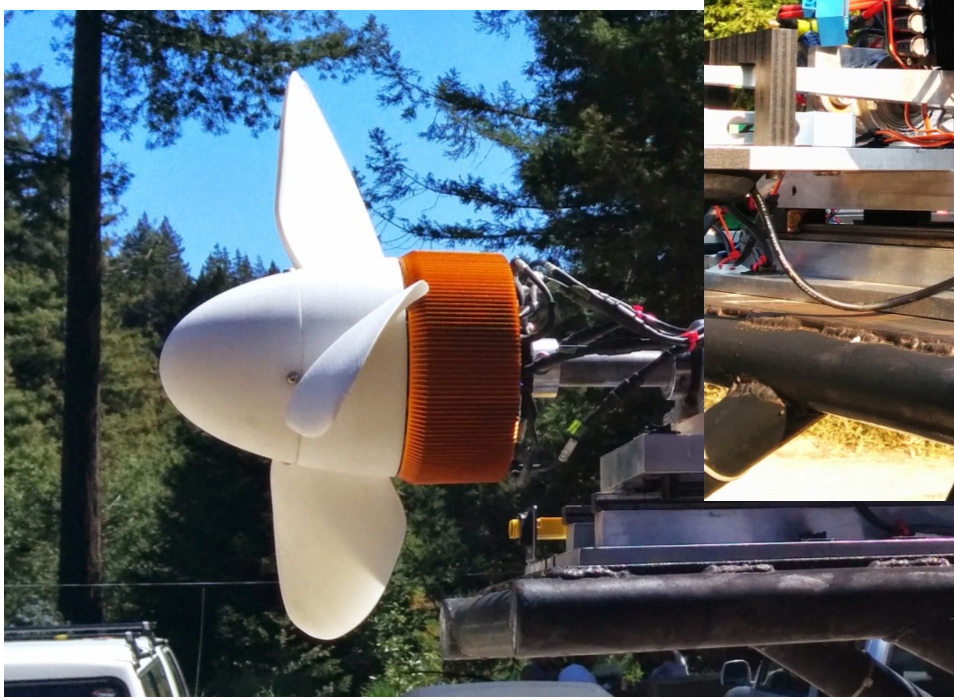
280A, 120V

Sensorless



Propeller

5 blade carbon



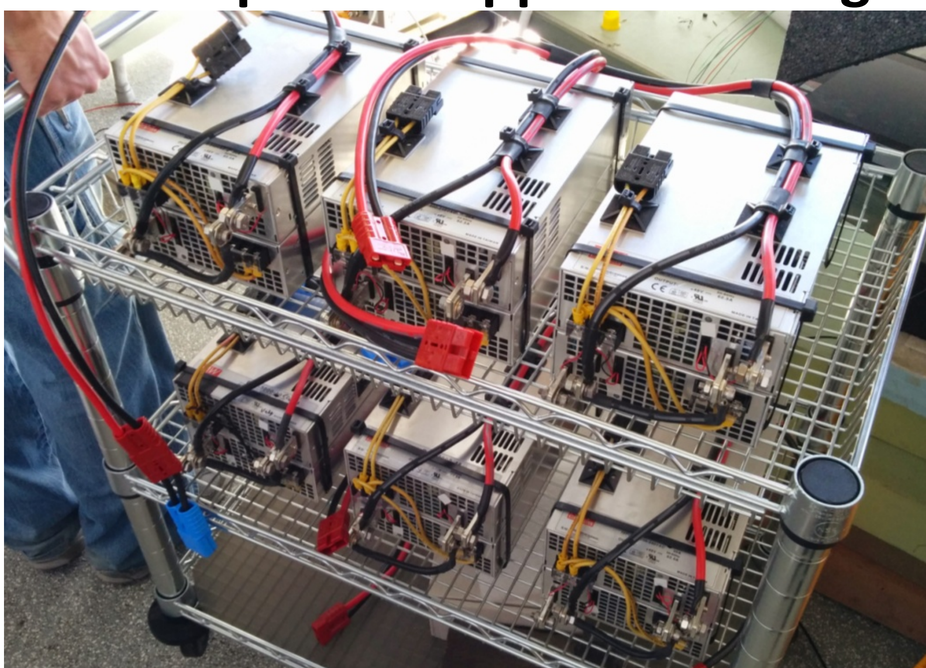
Batteries, Chargers

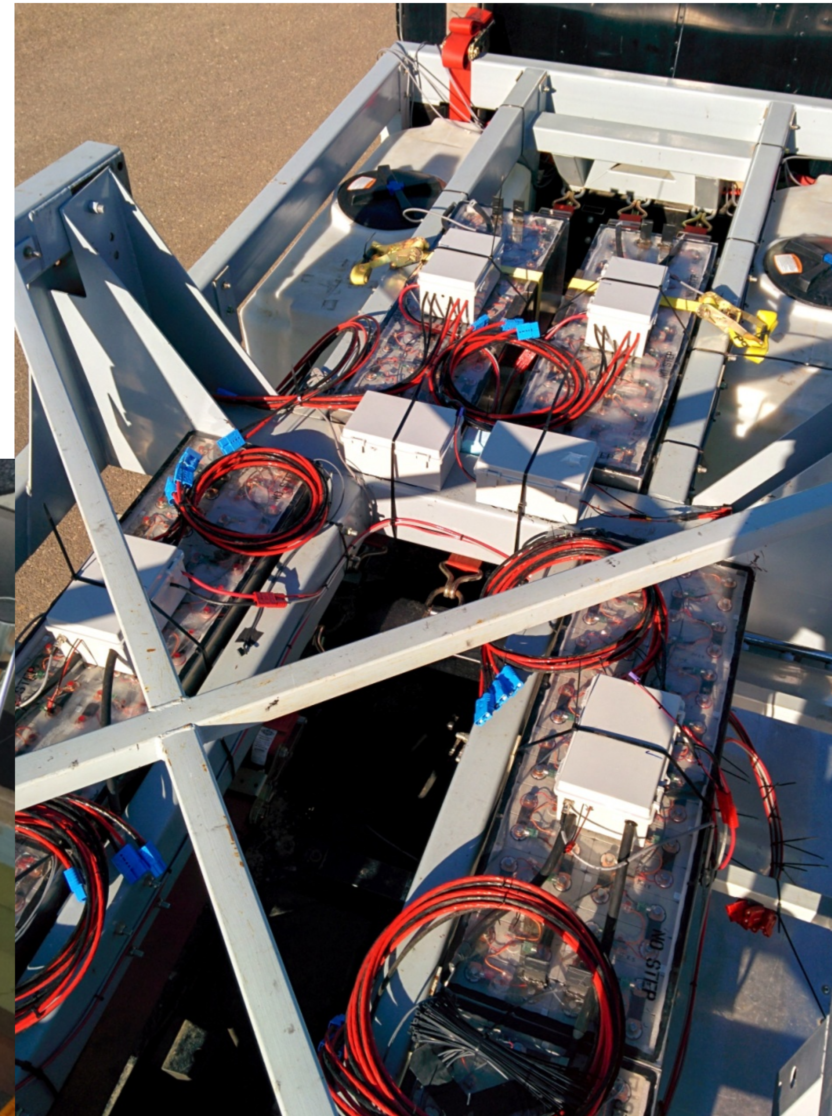
32 $LiFePO_4$ cells x6 packs

180 Ah

110 kWh

6x 6kW power supplies to charge





Testing

61kts

12kW shaft

6500rpm

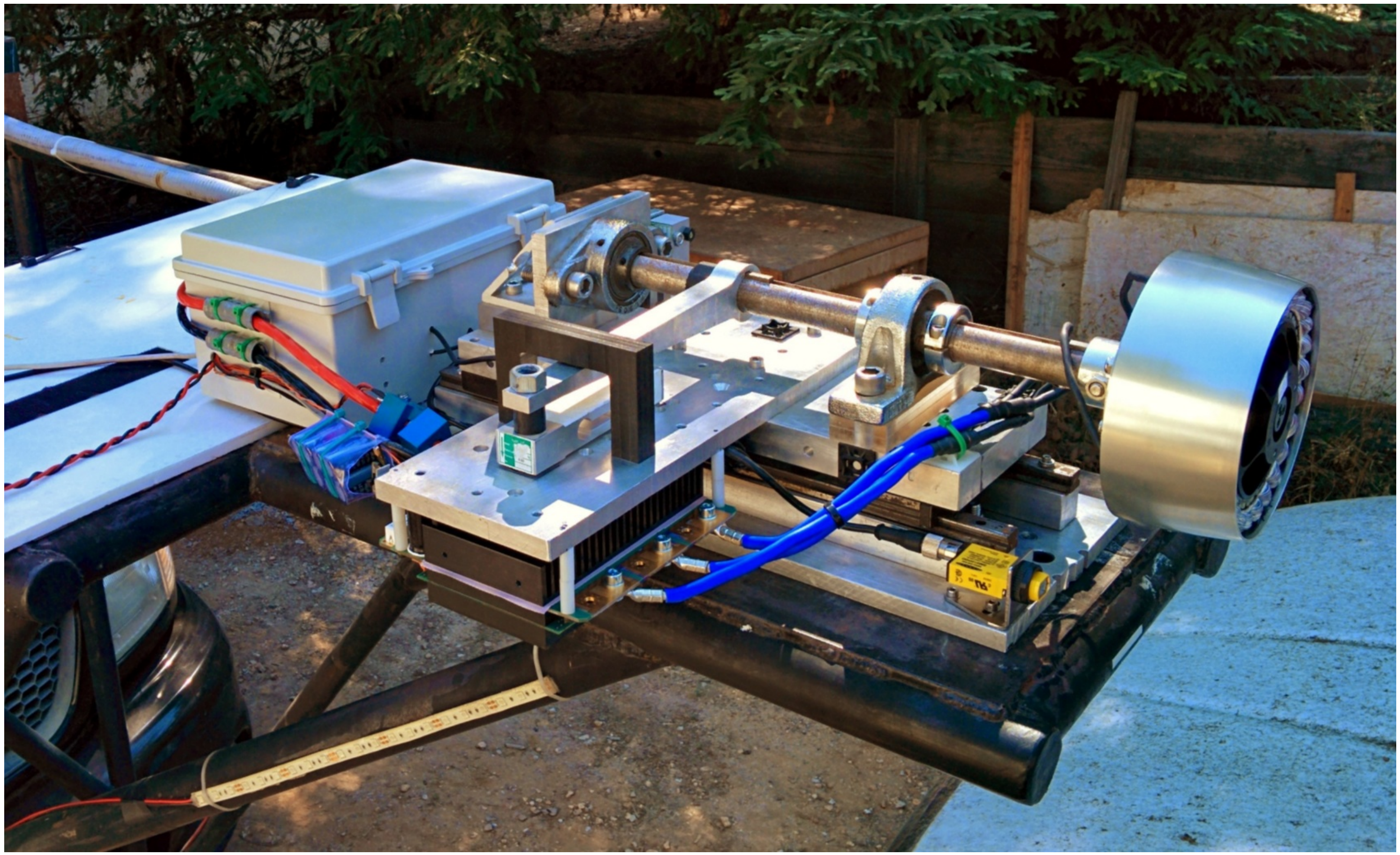
Current

Voltage

Thrust

Torque

RPM



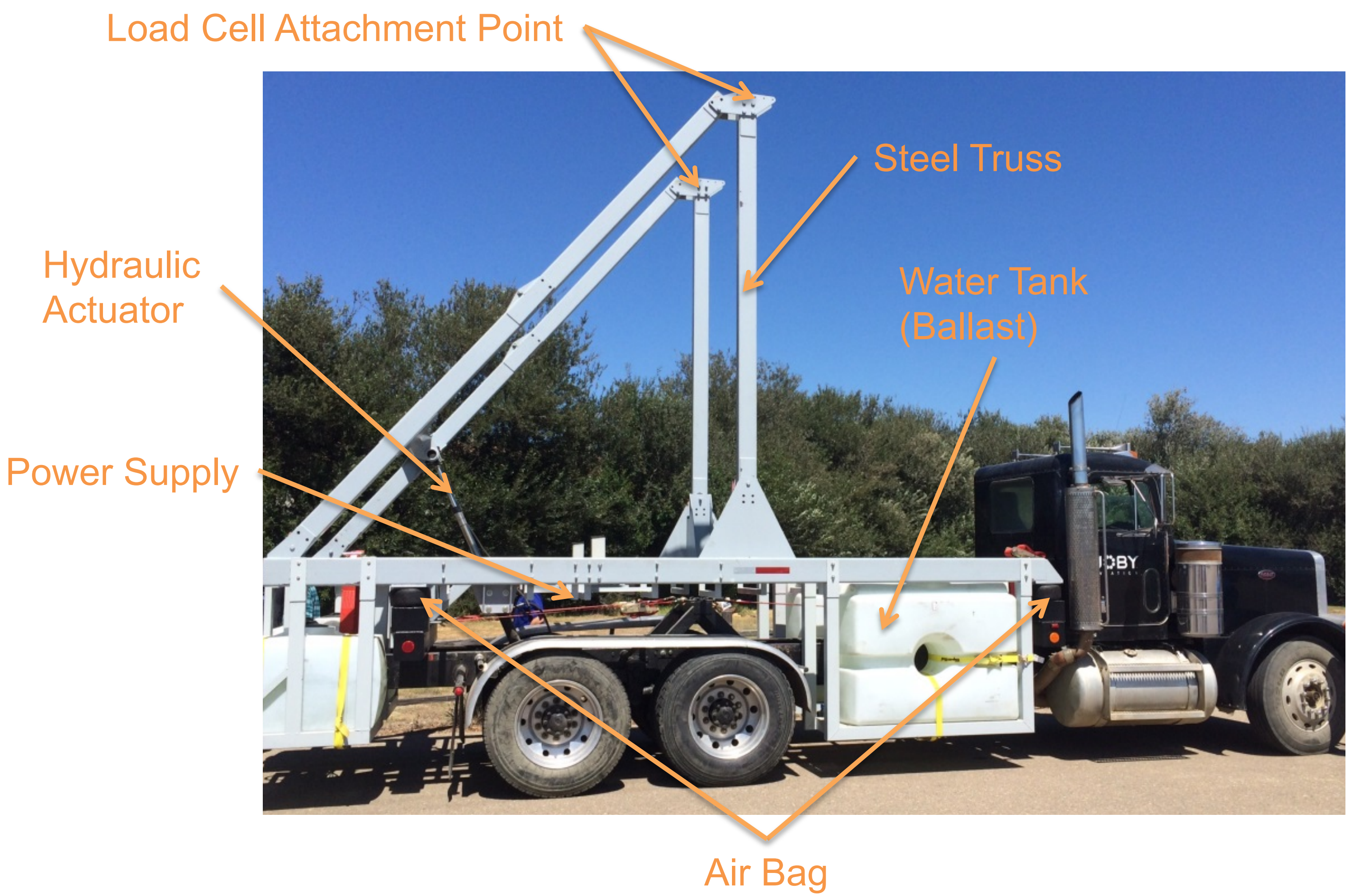
Truck Test Rig Wing Fabrication Integration

Alec Clarke, Joby Aviation

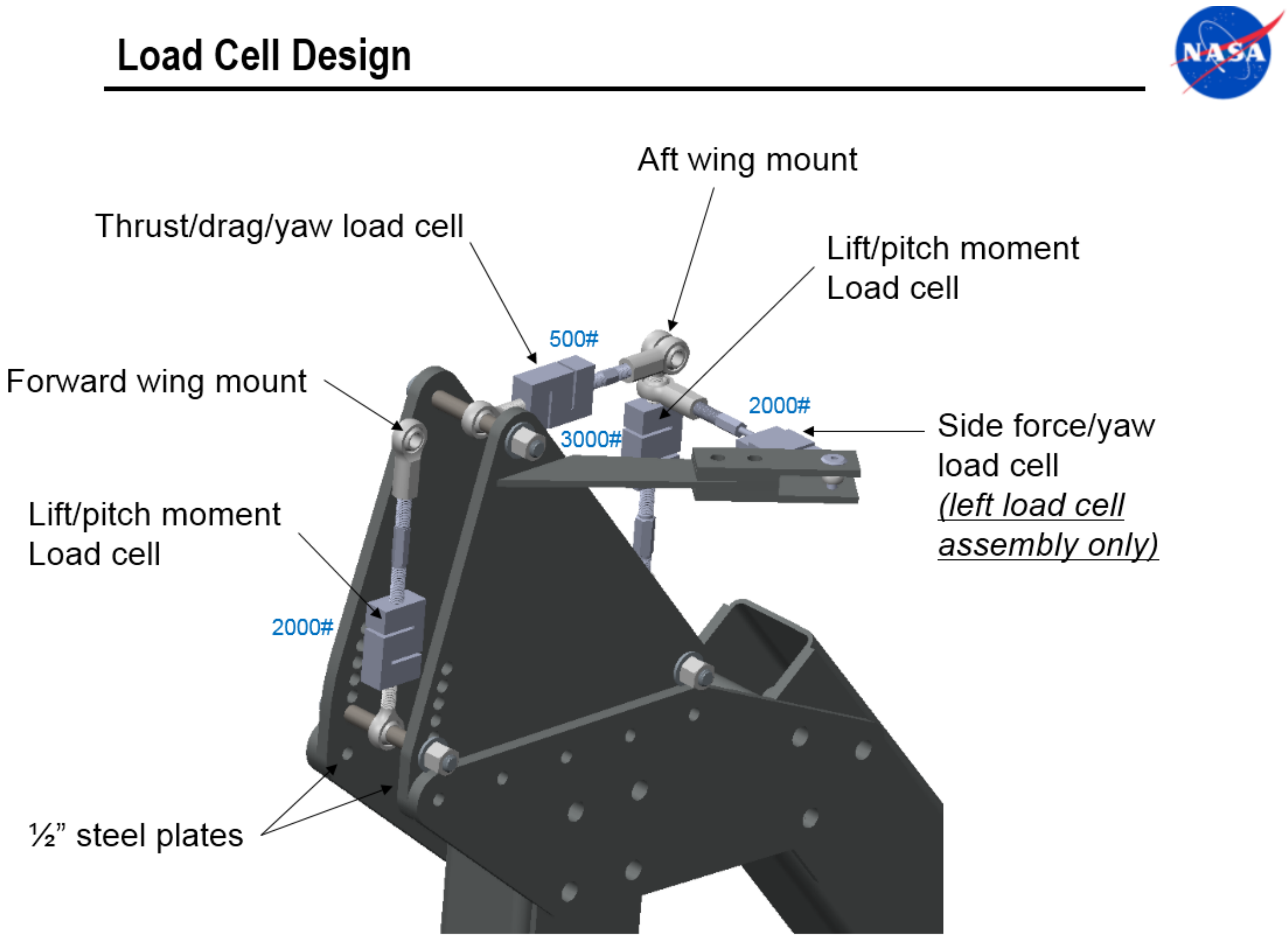
Truck Test Rig

- Converted Peterbilt truck
- Steel truss supports wing above the truck
- Load cells are mounted between the wing and the truss
- Airbag suspension isolates the truss assembly from road vibrations
- Onboard power supply to run the motors

Truck Test Rig - Outline



Load Cell Assembly

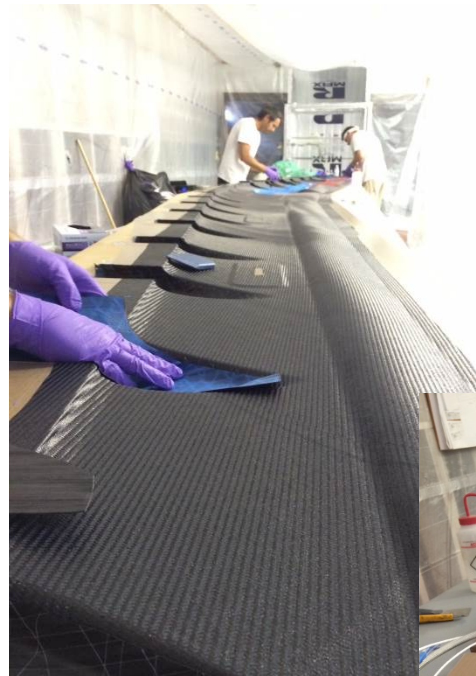


Left load cell assembly shown above – right assembly is similar

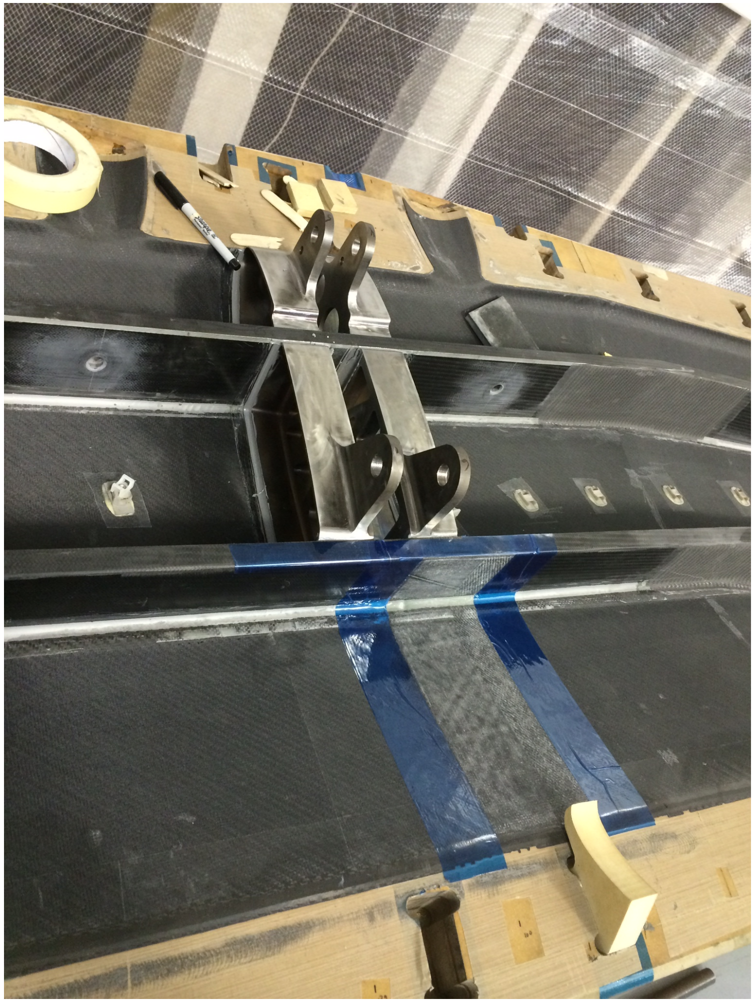
Truck with Lowered Structure

Wing Fabrication

- Carbon fiber wing
- Two skin design
- Dual spar configuration
- 18 Nacelles
  - Motors
  - Heatsink
  - props
- 6 access hatches
- Wing structural test to over 4000 lb



Wing Attachment Rib



Integration

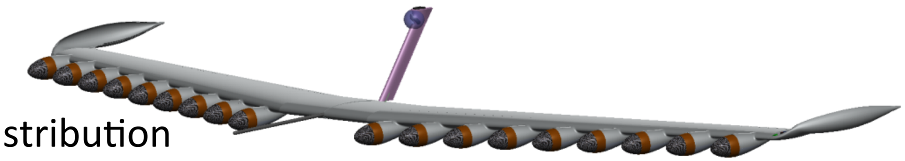
- Load cell assembly
- Wing attachment
- Power system wiring
- Instrumentation

Wing Instrumentation Calibration Testing Preparation

Trevor Foster, ESAero

Wing Instrumentation Design

Desired Areas of Measurement



- Aerodynamic Performance
  - Pressure strips for upper surface pressure distribution
  - High frequency pressure transducers for instantaneous pressure behind prop
  - Air data probe for airspeed and AoA
- Aerodynamic Forces
  - Load cells placed in an force balance system to acquire thrust, drag, lift, & yaw
- Aeroelasticity
  - Accelerometers at multiple locations
- Temperature of Electronic Components
  - Resistive Temperature Detectors (RTDs) place in key electronics for thermal monitoring
- Groundspeed
  - GPS unit to monitor ground speed
- Data Storage and Telemetry
  - Solid state hard drive for storage of video and sensor data
  - S-band antenna for telemetry
- Motor/Controller Performance
  - Motor and controller data gathered from CAN bus

Wing Instrumentation

Telectronics Miniature CAIS MCDAU-2000

(loaned by NASA Armstrong)

-Custom Force Balance with 7 Load Cells

-60 RTD Temperatures

-120 Pressure Measurements using Strip-A-Tubing

-8 High Speed Transient Pressures

-3 Uni, 3 Biaxial, 2 Triaxial Accelerometers

-Air Data Probe with Alpha & Beta

-Inclinometer

-3 HD Cameras

-GPS, S-Band Transmitter

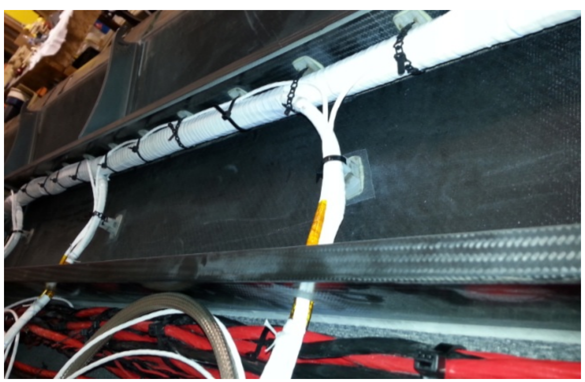
Wiring Harness Design

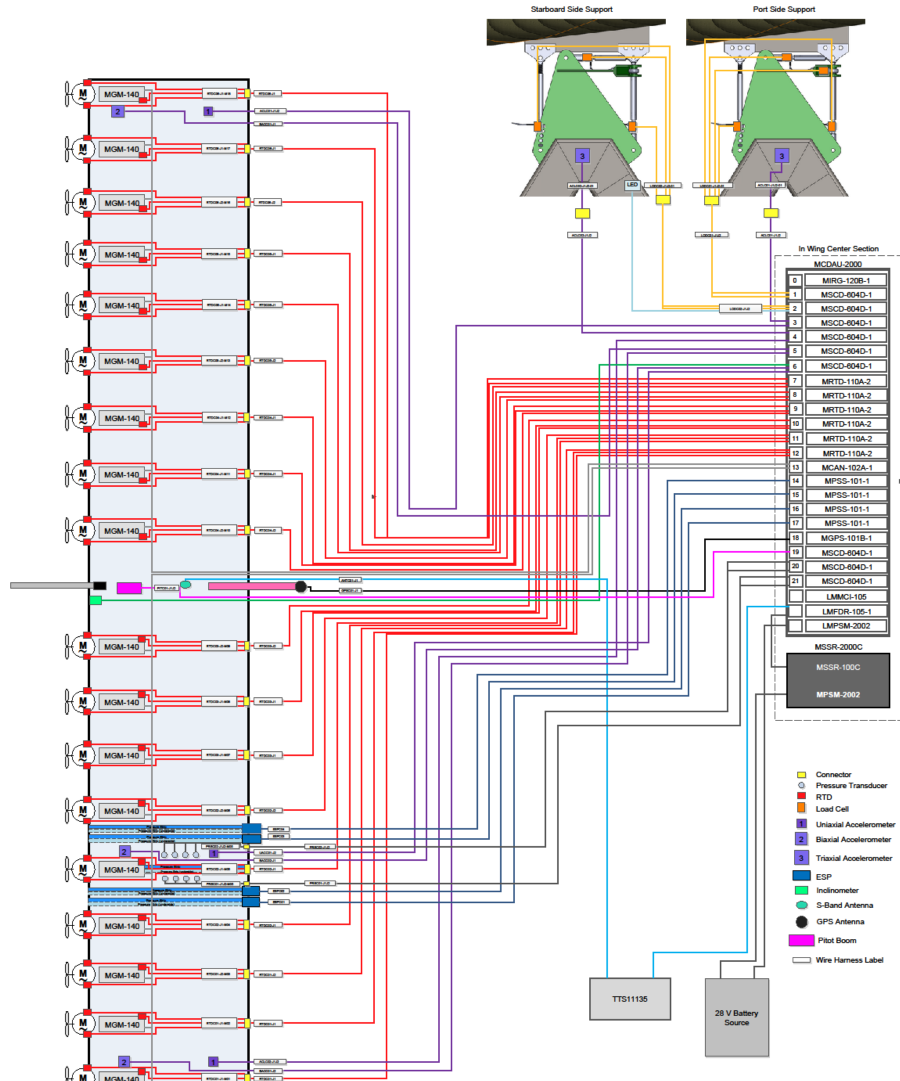
EMI Mitigation

- Dual Isolated Shields

- Harnesses and Connectors wrapped to prevent electrical contact with frame

-Sensors bonded to carbon frame have fiberglass base layer

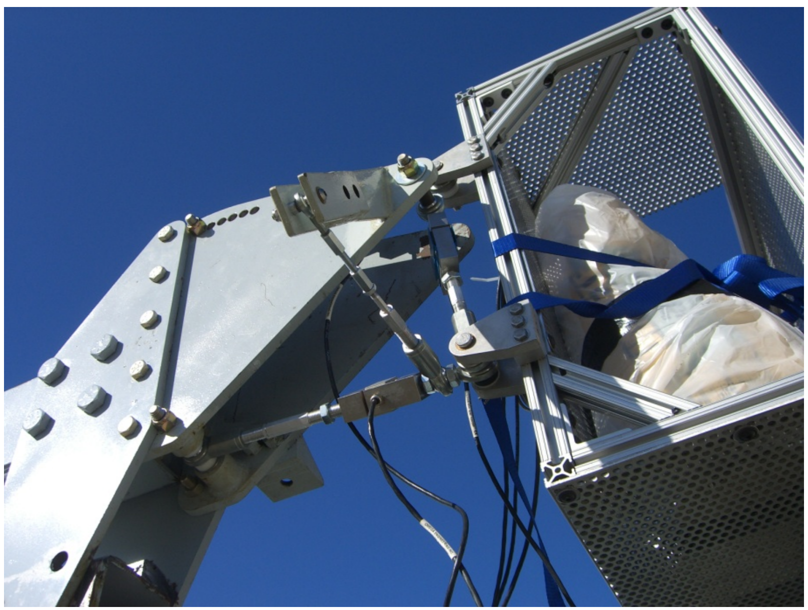




Early Validation

Instrumentation Platform

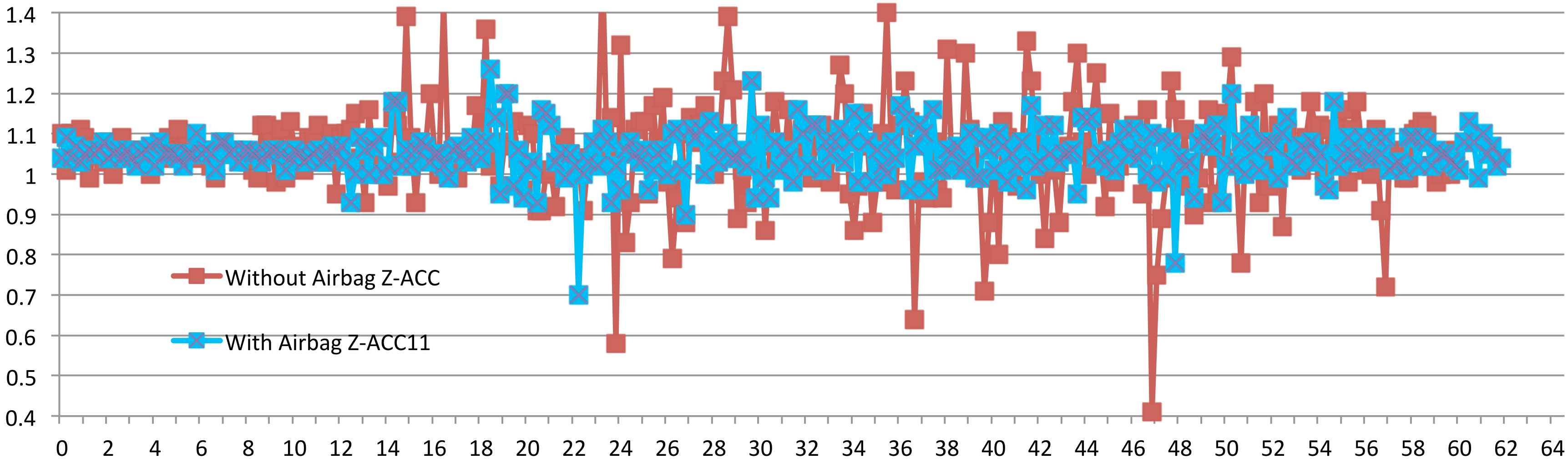
- Mass Simulator
- Test bed for DAQ/Sensors
- Practice for truck drivers



Ground Vibration Isolation

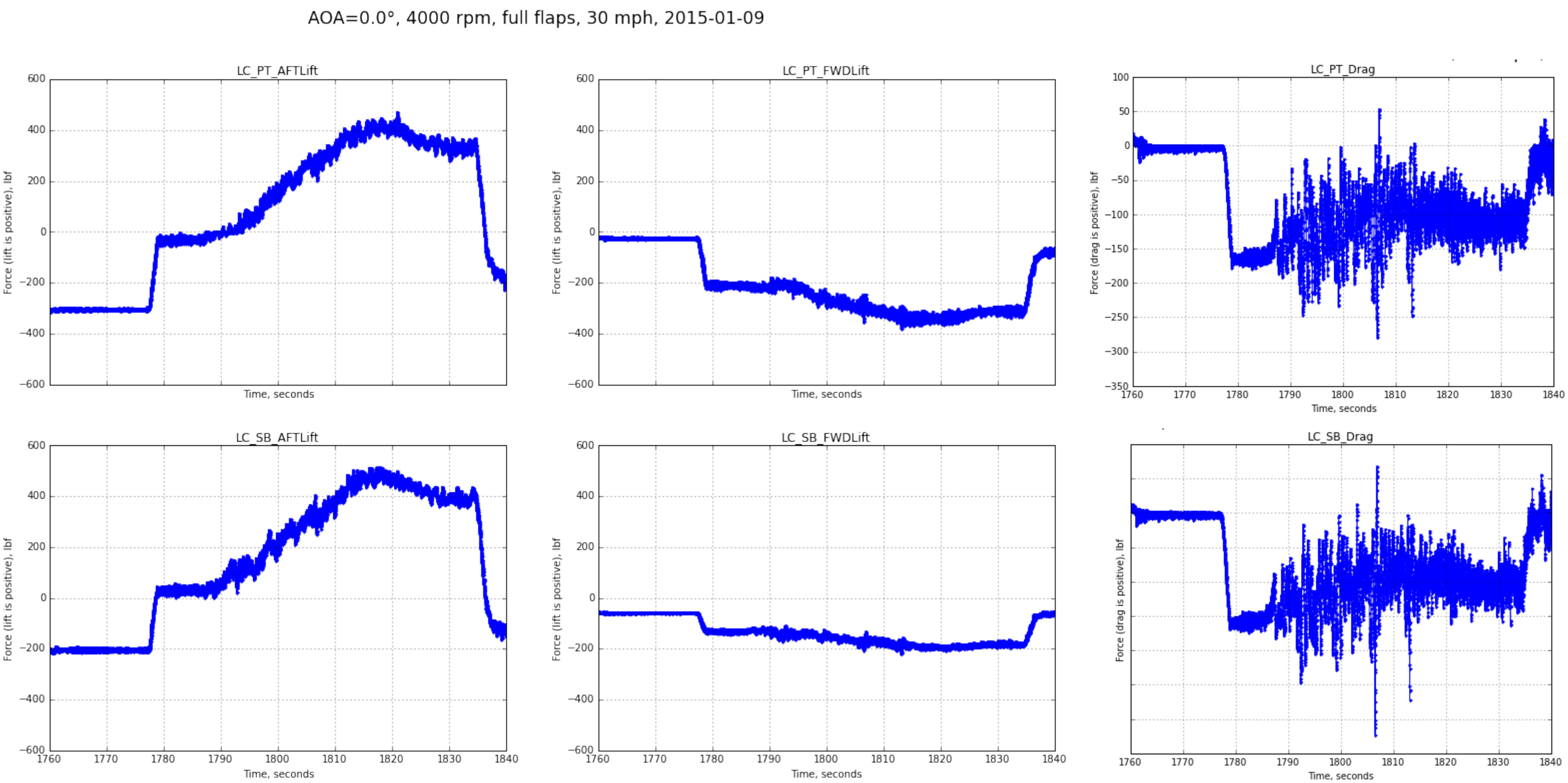
- Test stand is supported on truck bed by 4 Firestone Air Bags
- Up to 6 inches of vertical movement
- Side to side movement restricted by adjustable straps
- Video

Firestone 1T15M-2 Air Bag



Airbag Suspension Video

Initial Results



- Video

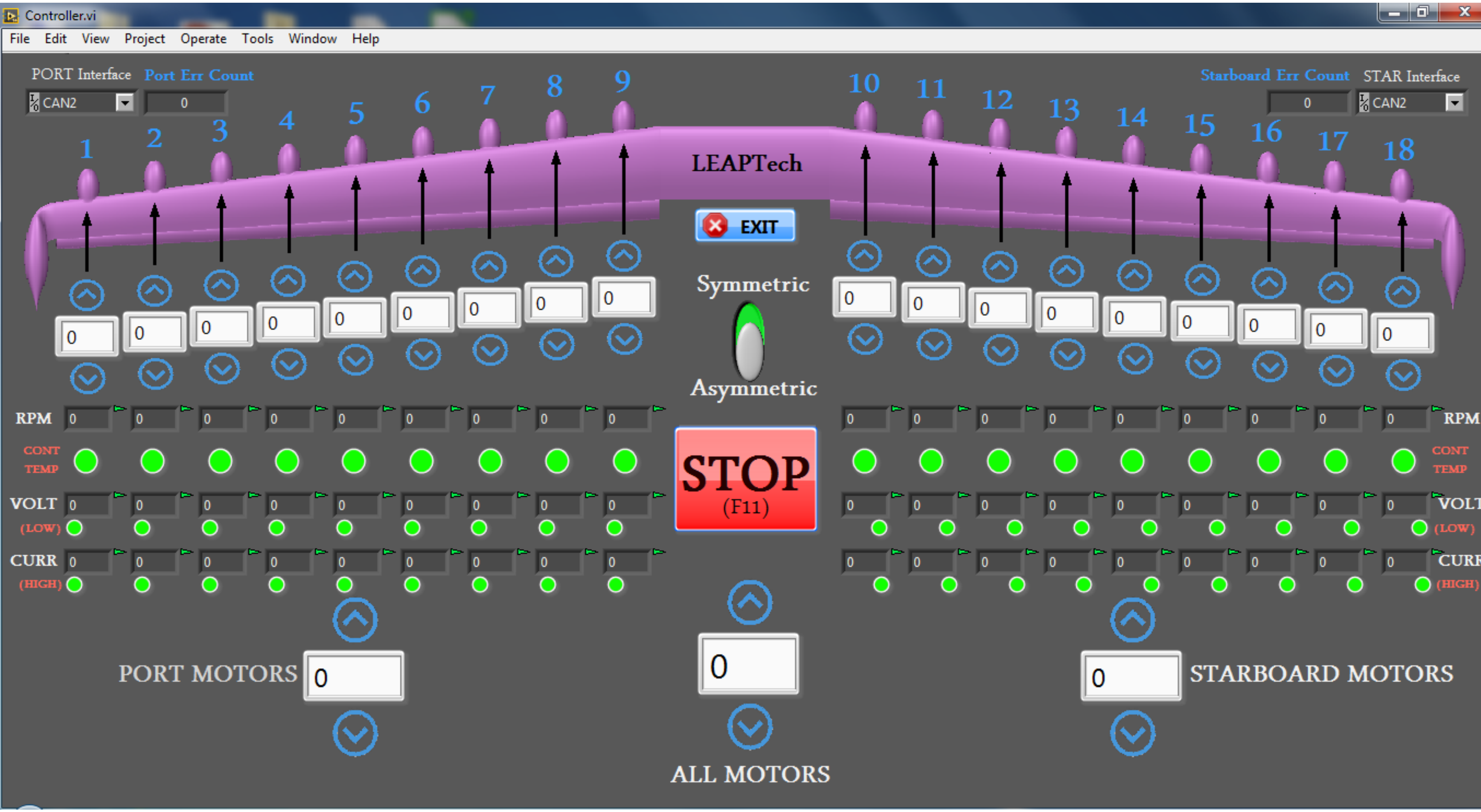
Power Control System Safety Review Initial Testing

Sean Clark, NASA AFRC

Power Control System

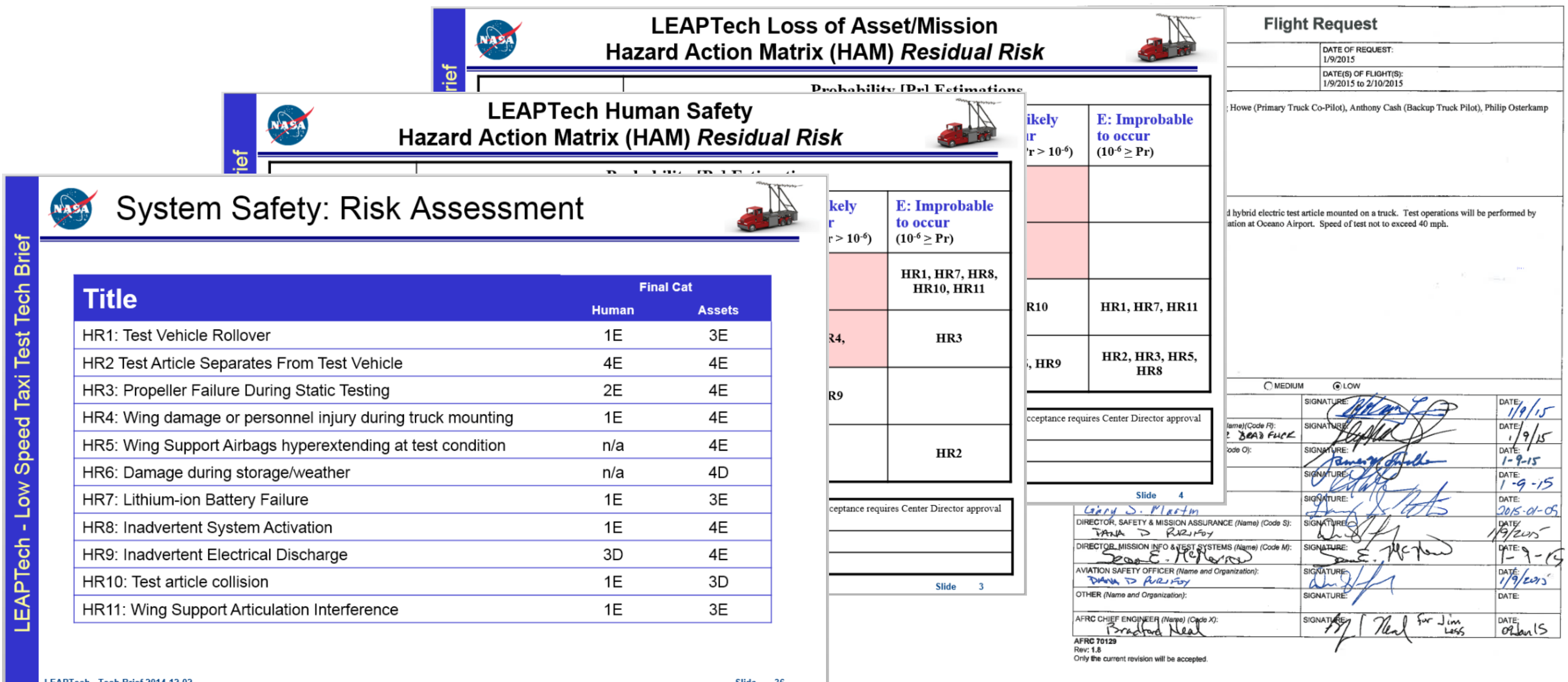
CAN bus (125 kBps, 21 nodes), Motor and BMS Telem., Speed cmds

Power System Control



Safety Review

- 11 Safety and Asset Hazards have been identified and mitigated
- Using the formal AFRC Tech Brief process for the Low Speed (Oceano) and High Speed (Edwards) Taxi Tests
- NASA SMEs have traveled to Joby and ESAero throughout the design, fab and integration phases to participate in subsystem reviews and procedures



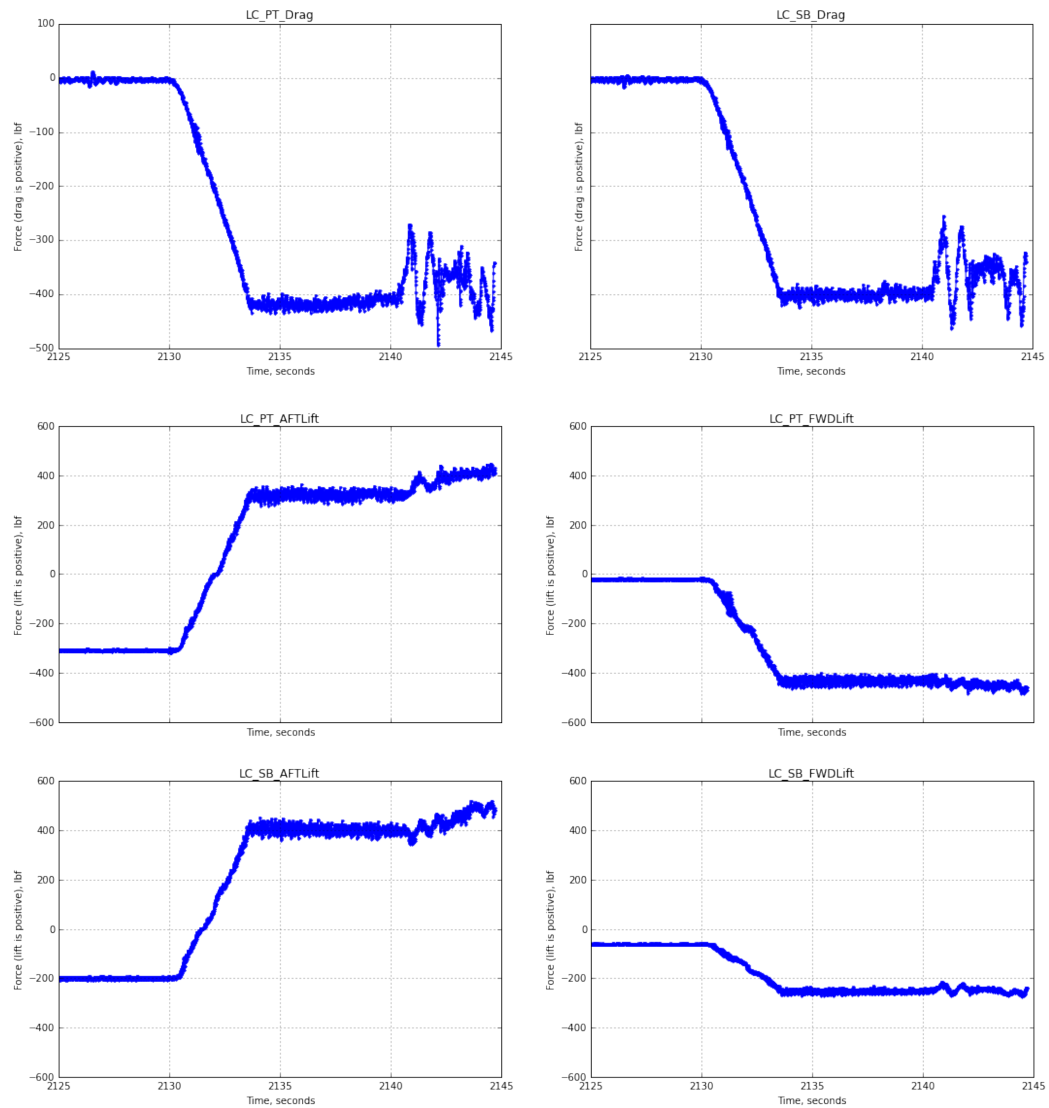
Title	Final Cat Human	Final Cat Assets
HR1: Test Vehicle Rollover	1E	3E
HR2 Test Article Separates From Test Vehicle	4E	4E
HR3: Propeller Failure During Static Testing	2E	4E
HR4: Wing damage or personnel injury during truck mounting	1E	4E
HR5: Wing Support Airbags hyperextending at test condition	n/a	4E
HR6: Damage during storage/weather	n/a	4D
HR7: Lithium-ion Battery Failure	1E	3E
HR8: Inadvertent System Activation	1E	4E
HR9: Inadvertent Electrical Discharge	3D	4E
HR10: Test article collision	1E	3D
HR11: Wing Support Articulation Interference	1E	3E

Initial Testing Results

- First stationary powered tests of the full wing were held in November 2014, but interference on the control bus prevented commanding to full power.

- Final harnesses were integrated and control system updates completed and final AFRC flight request signed off January 2015.

- Full power testing on the Oceana runway started on January 9, 2015.



Integrated System Testing Video

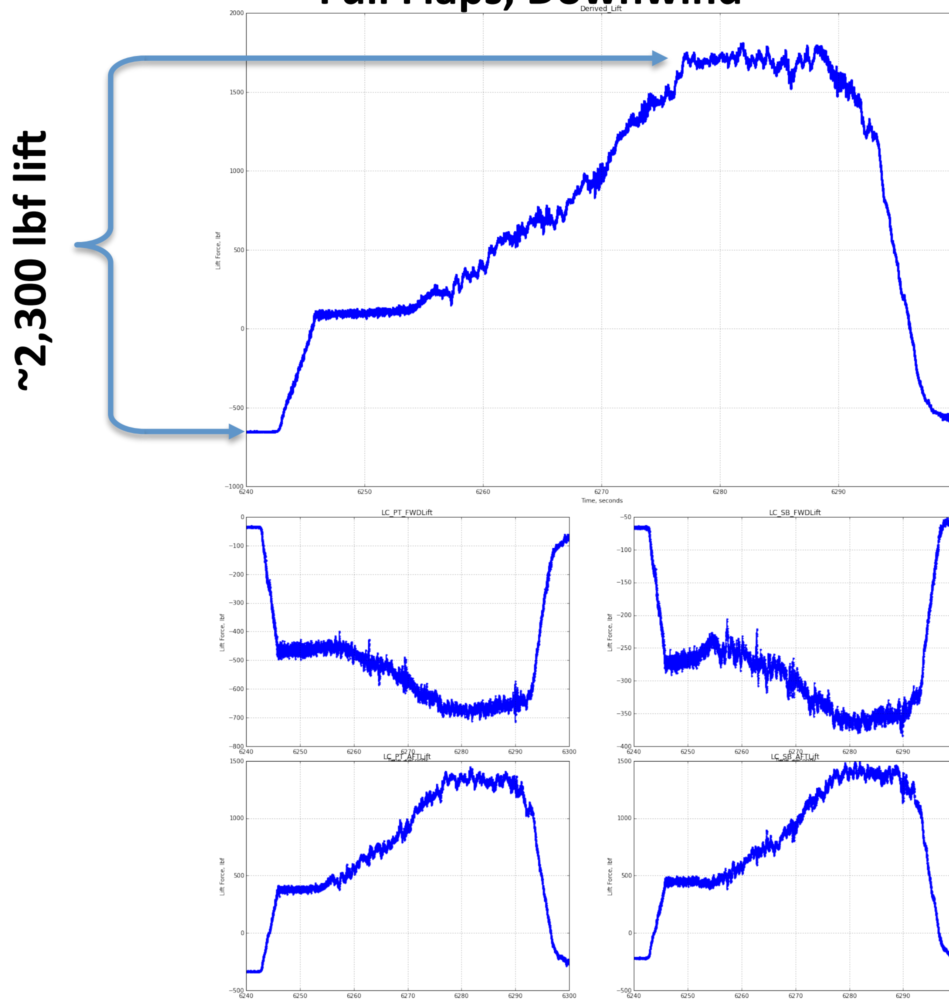
Early Test Results

Low Speed Taxi Testing in Oceano, CA is now underway; these measurements were collected on January 12, 2015

•Instrumentation system is 75% complete; Air Data probe, wing surface pressures and GPS are not yet integrated, so we can't account for winds on the airfield will increase/ decrease effective airspeed (and measured lift)

•Measured winds near the runway were between 6 mph and 8 mph during the test activity.

40 mph, 6400 rpm α=10°
Full Flaps, Downwind



Early Test Results

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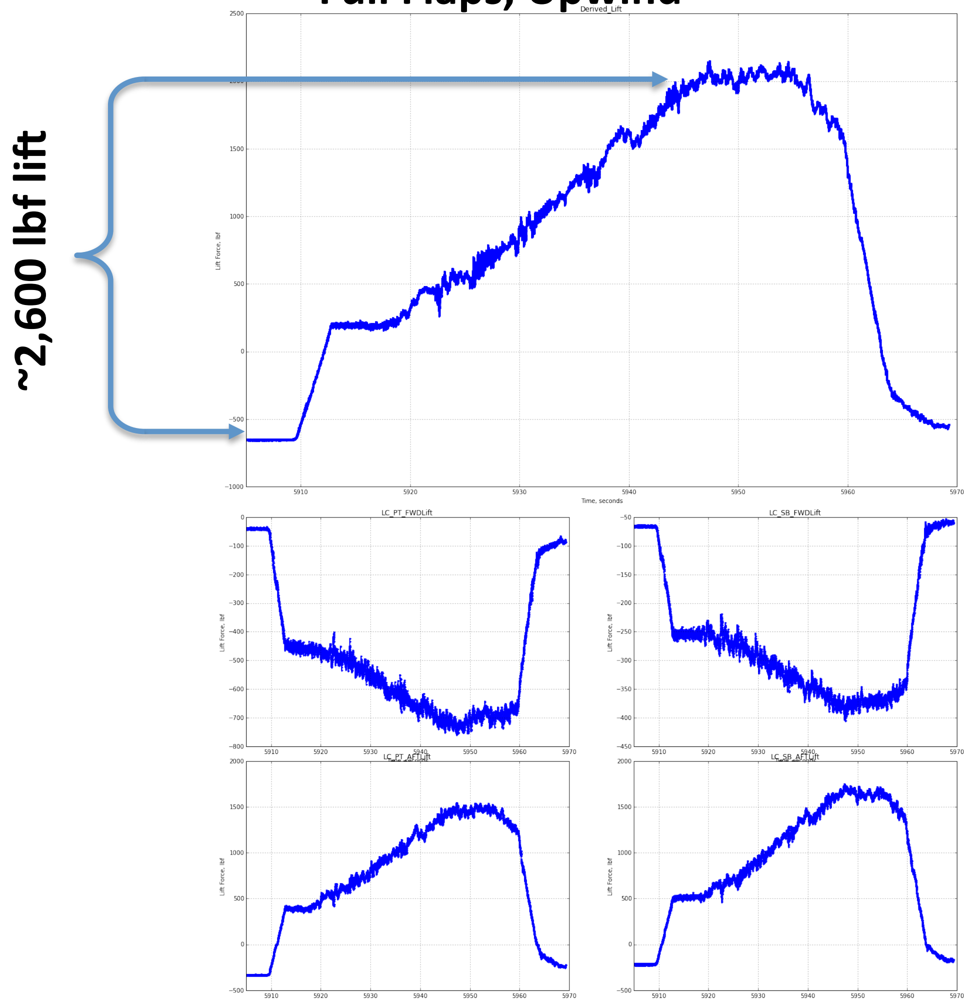
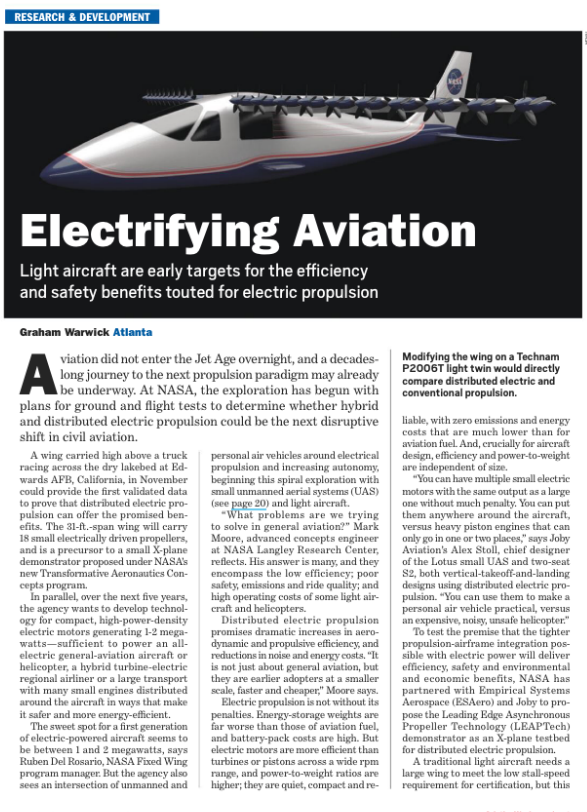
- **Measured winds near the runway were between 6 mph and 8 mph during the test activity.**

40 mph, 6400 rpm α=10°
Full Flaps, Upwind



Information Distribution

- (3) major 2-3 page articles published in Aviation Week and Aerospace America in 2014.
- A full session (5 papers) on LEAPTech has abstracts submitted for AIAA Aviation 2015.
- IEEE article and Smithsonian Air & Space articles are currently being written.



RESEARCH & DEVELOPMENT

Electrifying Aviation

Light aircraft are early targets for the efficiency and safety benefits touted for electric propulsion

Graham Warwick Atlanta

Aviation did not enter the Jet Age overnight, and a decades-long journey to the next propulsion paradigm may already be underway. At NASA, the exploration has begun with plans for ground and flight tests to determine whether hybrid and distributed electric propulsion could be the next disruptive shift in civil aviation.

A wing carried high above a truck racing across the dry lakebed at Edwards AFB, California, in November could provide the first validated data to prove that distributed electric propulsion can offer the promised benefits. The 31-ft.-span wing will carry 18 small electrically driven propellers, and is a precursor to a small X-plane demonstrator proposed under NASA's new Transformative Aeronautics Concepts program.

In parallel, over the next five years, the agency wants to develop technology for compact, high-power-density electric motors generating 1-2 megawatts—sufficient to power an all-electric general-aviation aircraft or helicopter, a hybrid turbine-electric regional airliner or a large transport with many small engines distributed around the aircraft in ways that make it safer and more energy-efficient.

The sweet spot for a first generation of electric-powered aircraft seems to be between 1 and 2 megawatts, says Ruben Del Rosario, NASA Fixed Wing program manager. But the agency also sees an intersection of unmanned and personal air vehicles around electrical propulsion and increasing autonomy, beginning this spiral exploration with small unmanned aerial systems (UAS) (see page 20) and light aircraft.

"What problems are we trying to solve in general aviation?" Mark Moore, advanced concepts engineer at NASA Langley Research Center, reflects. His answer is many, and they encompass the low efficiency; poor safety, emissions and ride quality; and high operating costs of some light aircraft and helicopters.

Distributed electric propulsion promises dramatic increases in aerodynamic and propulsive efficiency, and reductions in noise and energy costs. "It is not just about general aviation, but they are earlier adopters at a smaller scale, faster and cheaper," Moore says.

Electric propulsion is not without its penalties. Energy-storage weights are far worse than those of aviation fuel, and battery-pack costs are high. But electric motors are more efficient than turbines or pistons across a wide rpm range, and power-to-weight ratios are higher; they are quiet, compact and reliable, with zero emissions and energy costs that are much lower than for aviation fuel. And, crucially for aircraft design, efficiency and power-to-weight are independent of size.

Modifying the wing on a Technam P2006T light twin would directly compare distributed electric and conventional propulsion.

"You can have multiple small electric motors with the same output as a large one without much penalty. You can put them anywhere around the aircraft, versus heavy piston engines that can only go in one or two places," says Joby Aviation's Alex Stoll, chief designer of the Lotus small UAS and two-seat S2, both vertical-takeoff-and-landing designs using distributed electric propulsion. "You can use them to make a personal air vehicle practical, versus an expensive, noisy, unsafe helicopter."

To test the premise that the tighter propulsion-airframe integration possible with electric power will deliver efficiency, safety and environmental and economic benefits, NASA has partnered with Empirical Systems Aerospace (ESAero) and Joby to propose the Leading Edge Asynchronous Propeller Technology (LEAPTech) demonstrator as an X-plane testbed for distributed electric propulsion.

A traditional light aircraft needs a large wing to meet the low stall-speed requirement for certification, but this

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NASA Begins Tests On Distributed Electric Propulsion Rig

Unique NASA low-cost testbed for distributed electric propulsion is powered up

Graham Warwick | Aviation Week & Space Technology — Dec 1, 2014

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A truck-mounted wing will speed along a lakebed runway to measure lift increase from airflow through 18 electric-driven propellers on the leading edge.

NASA Photos

NASA already is learning about distributed electric propulsion from a unique low-cost testbed, as it completes high-power static tests ahead of low-speed taxi trials leading to high-speed runs on the dry lakebed at Edwards AFB, California, in January. As an initial step in the agency's proposed plan to fly an X-plane distributed-propulsion demonstrator, the Hybrid Electric Integrated Systems Testbed (Heist) is a truck-mounted rig built to enable NASA to ground-test a full-scale wing ...

Engineering Notebook

The power of electricity

A team of NASA and industry engineers is almost ready to start ground testing a wing and propeller system that could point the way toward the first electrically propelled commuter and general aviation planes. **Ben Iannotta** *tells the story of LEAPTech, the Leading Edge Asynchronous Propellers Technology project.*

[illegible] a NASA technician will hop in the cab of a large truck and accelerate across a California dry lake bed to a speed of 70 miles per hour, pulling a 31-foot carbon composite wing span attached to a hydraulic jack. The wing will stay on the truck while 18 propellers whirl, powered by motors and lithium phosphate batteries.

The 12,000-foot run is to be the first of many across the dry lake and will mark the start of a new phase of a project called LEAPTech, short for Leading Edge Asynchronous Propellers Technology — asynchronous because each LEAP motor can be operated at a different speed. The researchers hope to show that the noise from all those propellers can be rendered less annoying for people on the ground by running them at slightly different revolutions per minute. The wing, designed by NASA and Joby Aviation of Santa Cruz, Calif., will be laced with pressure and other sensors to measure the effects of the air rushing over it as it is accelerated by the 18 propellers.

LEAPTech is a key element of

Desert runner: This refurbished water truck will carry an experimental wing and electric propellors across a dry lake to simulate various flight angles.

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Next Steps

- Initial testing will continue at Oceana Airfield in San Luis Obispo through the end of Jan to ensure all instrumentation is working well.
- High speed testing at typical General Aviation 61 knot stall speeds will begin at NASA AFRC in February.
- Extensive failure mode testing will be conducted as part of developing a full DEP aerodynamic database in March/April.
- Motor controllers will be replaced in May/June to permit spread frequency and phasing acoustic experiments (providing an initial experimental dataset to NASA TAC/TTT DEP acoustic research).
- All research will provide significant value and risk reduction as this research transitions to NASA TAC/CAS Convergent Electric Propulsion flight demonstrator project.

Questions?

THANK YOU to an incredibly talented, enthusiastic and energetic team, with too many researchers to list individually.

Thanks to Joby, AFRC, ESAero and LaRC IRAD, for cost sharing; without this we never could have accomplished so much.

Thanks to NARI for taking a chance on such an aggressive research proposal that few believed could be accomplished in 1 year.

Thanks to the NASA TAC/CAS Project for taking this research to the next stage.